Institute of Water Research
Annual Technical Report
FY 2005

Introduction

The Institute of Water Research (IWR) at Michigan State University (MSU) continuously provides timely information for addressing contemporary land and water resource issues through coordinated multidisciplinary efforts using advanced information and networking systems. The IWR endeavors to strengthen MSUs efforts in nontraditional education, outreach, and interdisciplinary studies utilizing available advanced technology, and partnerships with local, state, regional, and federal organizations and individuals. Activities include coordinating education and training programs on surface and ground water protection, land use and watershed management, and many others. (An extended introduction can be found in our FY2001 Annual Technical Report.) We also encourage accessing our web site which offers a more comprehensive resource on IWR activities, goals, and accomplishments: www.iwr.msu.edu.

The Institute has increasingly recognized the acute need and effort for multi-disciplinary research to achieve better water management and improved water quality. This effort involves the integration of research data and knowledge with the application of models and geographic information systems (GIS) to produce spatial decision support systems (SDSS). These geospatial decision support systems provide an analytical framework and research data via the web to assist individuals and local and state government agencies make wise resource decisions. The Institute has also increasingly become a catalyst for region wide decision-making support in partnership with other states in EPA Region 5 using state-of-the-art decision support systems.

The Institute also works closely with the MSU Cooperative Extension Service to conduct outreach and education. USGS support of this Institute as well as others in the region enhances the Institute credibility and facilitates partnerships with other federal agencies, universities, and local and state government agencies. The Institute also provides important support to MSU-WATER, a major university initiative dealing with urban stormwater issues with funding from the university Vice President for Finance. A member of the Institutes staff works half-time in facilitating MSU-WATER activities so the Institute enjoys a close linkage with this project. The following provides a more detailed explanation of the Institutes general philosophy and approach in defining its program areas and responsibilities.

General Statement
To deal successfully with the emergence of water resource issues unique to the 21st century, transformation of our knowledge and understanding of water for the protection, conservation, and management of water resources is imperative. Radically innovative approaches involving our best scientific knowledge, extensive spatial databases, and intelligent tools that visualize wise resource management and conservation in a single holistic system are likewise imperative. Finally, holistic system analysis and understanding requires a strong and integrated multi-disciplinary framework

Research Program
The management of water resources, appropriate policies, and data acquisition and modeling continue to be at the forefront of the State Legislatures agenda and numerous environmental and agricultural

organizations. Our contribution to informing the debate involved numerous meetings, personal discussions, and most importantly, the enhancement of web-based information to aid in the informed decision-making process.

Unique Capabilities: Decision Support Systems as the Nexus
IWR, with its extended research family, is exceptionally well-positioned to integrate research conducted within each of the three principal water research domains: hydrologic sciences, water resources, and aquatic ecosystems. Integrated decision support both reflects and forms the nexus of these three research domains. Expanding web accessibility to the decision support system nexus (formed by the intersection of the three research domains) will facilitate broad distribution of science-based research produced in these domains.

The Institutes extensive experience in regional and national networking provides exceptional opportunities for assembling multi-agency funding to support interdisciplinary water research projects and multi-university partnerships.

Using A Multi-Disciplinary Framework
Using a multi-disciplinary framework facilitates dynamic applications of information to create geospatial, place-based strategies, including watershed management tools, to optimize economic benefits and assure long-term sustainability of valuable water resources. New information technologies including GIS and computational analysis, enhanced human/machine interfaces that drive better information distribution, and access to extensive real-time environmental datasets make a new intelligent reality possible.

Effective watershed management requires integration of theory, data, simulation models, and expert judgment to solve practical problems. Geospatial decision support systems meet these requirements with the capacity to assess and present information geographically, or spatially, through an interface with a geographic information system (GIS). Through the integration of databases, simulation models, and user interfaces, these systems are designed to assist decisionmakers in evaluating the economic and environmental impacts of various watershed management alternatives.

The ultimate goal of these new imperatives is to secure and protect the future of water quality and supplies in the Great Lakes Basin and across the country and the worldwith management strategies based on an understanding of the uniqueness of each watershed.

Research Program

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Natural Resources Integrated Information System

Basic Information

Title:	Natural Resources Integrated Information System
Project Number:	2005MI57B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	8th
Research Category:	Water Quality
Focus Category:	Groundwater, Surface Water, Water Quantity
Descriptors:	Data Analysis, Data Storage and Retrieval, Information Dissemination, System
Principal Investigators:	Jon Bartholic

Publication

1. Ouyang, D., J. Bartholic, and J. Selegean. 2005. Assessing Sediment Loading from Agricultural Croplands in the Great Lakes Basin. The Journal of American Science, Vol. 1(2): pp. 14-21.
2. Shi, Y., J. Bartholic, A.J. Asher, J-Y Choi, B. Engel, R. Farnsworth. 2005. An On-line Web GIS-based Hierarchical Watershed Decision Support System for United States, ISEIS 2004 International Conference, Journal of Environmental Informatics Archives, ISEIS Publication #002, Volume 2 (2004), pp. 838-845.
3. Zorn, T., P.W. Seelbach, and M.J. Wiley 2002. Distributions of Stream Fishes and their Relationship to Stream Size and Hydrology in Michigans Lower Peninsula. Transactions of the American Fisheries Society 131: 70-85

Project Number: 2005MI57B
Start: 03/01/05 (actual)
End: 02/28/06 (actual)
Title: Natural Resources Integrated Information System
Investigators: Jon F. Bartholic, Institute of Water Research, Michigan State University
Focus Categories: M & P, WQL, MOD
Congressional District: eighth
Descriptors: Data Analysis, Data Storage and Retrieval, Information Dissemination, System Analysis, Geographic Information Systems, Water Quality Management, Watershed Management

Areas of Relevant Research

The management of water resources, appropriate policies, and data acquisition and modeling continue to be at the forefront of the State Legislature's agenda and numerous environmental and agricultural organizations. Our contribution to informing the debate involved numerous meetings, personal discussions, and most importantly, the enhancement of web-based information to aid in the informed decision-making process.

Results and Benefits

Extensive investigation and research is needed to achieve effective coupling of human management needs with geospatial databases and decision support systems to assist better decision-making. Multiple research funding opportunities exist to support linking understanding of various phases of the hydrologic cycle with impacts on water use, management, and conservation. As a result, outstanding opportunities to develop scientific water management skills and techniques for the 21st Century are clearly within reach.

Development of geospatial decision support systems complement and build on the extensive scientific knowledge of the role of the hydrologic balance in the functioning of dynamic ecosystems. Based on current development of geospatial databases and modeling systems, a model of the hydrologic balance for the state can be developed to assist water management and conservation. By incorporating extensive geospatial data with the analytical capacity of decision support systems, university researchers are providing decision-makers and managers with a more refined understanding of the hydrologic cycle and water balance functions at watershed and statewide scales.

Our USGS investments over the past two years led to a two-year $540,000 grant from the Great Lakes Protection Fund awarded to Michigan State University and the Institute of Water Research (IWR) for a project entitled "Restoring Great Lakes Basin Waters Through the Use of Conservation Credits and an Integrated Water Balance Analysis System." The IWR is responsible for coordinating and collaborating multidisciplinary teams from various organizations including the World Resources Institute, Institute for Fisheries Research of the Michigan Department of Natural Resources, Public Sector Consultants of Lansing, US Geological Survey District Office, and MSU Departments of Agricultural Economics, Biosystems and Agricultural Engineering; Geography, Civil and Environmental Engineering; and the Community, Agriculture, Recreation and Resource Studies (CARRS).

The project will integrate three systems --Water Conservation Credit, Water Balance Analysis, and the User Assistance Interface, into a single Water Conservation Credits Implementation package. Large water users, including municipalities, corporations, and irrigation users, who are considering major new withdrawals can benefit from the Water Conservation Credits Implementation package by being able to access information on the watershed in which they have an interest, and use this information in their management decisions to guide potential conservation transactions. Individually, the Water Conservation Credits System provides analyses to support the development of an innovative system of water conservation credits which will help policy makers manage water resources to meet the demands of water uses, conservation, and the improvement of ecological sustainability. The Water Balance Analysis System integrates three existing hydrological models that incorporate surface, groundwater, and stream aquatic ecosystem models. The User Assistance Interface System couples the hydrologic models with spatial data to allow a decision maker to create various scenarios for management of water resources in Michigan and the Great Lakes Basin. Combined, these systems can be used to assess the ecological vulnerability of watersheds, the impacts of wells on groundwater levels, river and ecosystems, the effectiveness of conservation practices and associated water conservation credits, and other issues. State agencies in the Great Lakes Basin who are responsible for the improvement of water resources and the health of the Greater Lakes Basin ecosystems can use the system package to support development and implementation of state and regional water management policies. Products will be designed as simple online tools by integrating information and models with appropriate interfaces to the water analysis system. The entire study process is guided with inputs from an Advisory Team composed of leaders from a wide set of interest areas.

The policy impact of this project has been immediate, significant, and perhaps even profound. Our project influenced the final shape of landmark legislation signed into law February 28 that establishes a comprehensive framework for the management of water resources in the state of Michigan. Moreover, findings and results from our project will provide policy-relevant scientific research and new tools to inform the implementation of state water policy, including making future policy recommendations by July 1, 2007 specified in P.A. 34 (2006) for the sustainability of state groundwater use, development of sustainability indicators to evaluate sustainability of state groundwater use, determining whether certification requirements are needed for groundwater withdrawals to assure conformance with Annex 2001, determining whether conservation programs should include mitigation of adverse impacts of water withdrawals on state waters and water-dependent natural resources, and other critical areas. Equally important, this state legislation puts Michigan in accordance with the provisions of the Great Lakes Charter Annex 2001 so that the innovations in our development of state water resource decision-making and related tools will potentially have application across the Great Lakes Basin. Many of our Advisory Team members contributed to the passage of this legislation and will be involved in the implementation of this new comprehensive water policy framework. Our Advisory Team provided an excellent conduit through which the knowledge and development of our project has informed the legislative process and will inform the policy making process in the future.

IWR and its partners are expected to participate in the design of a water withdrawal assessment tool as specified by the P.A. 34 (2006) that will incorporate state-of-the-art and real-time scientific research to guide and assist the permitting of large-capacity water withdrawals. This assessment tool must be designed to evaluate the impacts of water withdrawals on nearby streams and/or aquatic-dependent natural systems and whether a proposed withdrawal may cause an adverse impact on state waters or aquatic-dependent resources. We envision a major role for our Project Team, in cooperation with other researchers and stakeholders, to develop this assessment tool by using the results from the preliminary development of computer sub-models developed for this project.

In addition to a significant role in developing the assessment tool, we anticipate a major role in using the results of our project for application in a new water use conflict resolution process. Those seeking permits for large quantity withdrawals are encouraged by the new legislation to establish a Water User Committee for that permit to evaluate current water resources, water uses, and trends in water use in the watershed and assist in long-term water resource planning in the watershed. Water User Committees will include all water withdrawal registrants, water withdrawal permit holders, and local government officials in the watershed. Solutions to water use conflicts developed by these committees could include water conservation offset credit as pioneered by this project. While this committee process is not required, it will certainly behoove any permit seeker to follow this process in light of Michigan's recent history with time-consuming court cases and formidable public opposition to large water withdrawals.

The new legislation also calls for the state Department of Environmental Quality (DEQ) to use "clear and convincing scientific evidence" in determining whether adverse resource impacts "are, or are likely, to occur from one or more large-quantity withdrawals in the watershed." The DEQ will be responsible for notifying the watershed Water Users Committee or meeting with water use registrants and water withdrawal permit holders to attempt facilitation of an agreement for using voluntary measures to prevent adverse resource impacts.

We anticipate that the findings regarding our voluntary, water conservation offset credit approach may be directly applied to create a science-supported scheme that accommodates all water users and avoids costly, time-consuming legal conflicts and divisive dissatisfaction in the community. By integrating our data into a readily-usable and web-accessible system for Water User Committees, timely and valuable information will be delivered to those who need it most. Future opportunities appear abundant for assisting the local watershed conflict resolution process and for creating viable options, including offsets and conservation credits, to prevent adverse resource impacts. These scenarios will be supported by science-based research supported by the GLPF.

The bottom line shows a unique convergence of our NIWR/USGS and the Great Lakes Protection Fund project with the implementation of recently-enacted state legislation and with the next phase of state policy making. As prescribed in recent legislation, a set of policy recommendations addressing the sustainability of groundwater will be submitted by the Groundwater Conservation Advisory Council (GCAC) July 1, 2007 and the GCAC process needs to be informed by hard science and knowledge of state water resources and watershed management. In addition, the Groundwater Conservation Advisory Council is responsible for guiding the overall implementation of the legislative mandates for related water policy development as well designing the water withdrawal assessment tool. As some members of our project Advisory Committee serve on the Groundwater Conservation Advisory Council, a robust linkage provides an important mechanism for the Institute's role in developing the assessment tool and assisting in conflict resolution processes.

Our web-based offerings continue to expand. A Nation-Wide Digital Watershed web site has been developed to allow individuals from across the United States locate themselves by using their address, watershed, or by regional areas established by the EPA. The illustration shows the software developed in the IWR that can be applied to a national situation. The data used in the system was acquired from EPA Basin data via the web. The site for Michigan allows users to zero-in on the eight-digit watersheds and then down to the 12-digit watershed system known as "Know Your Watershed." A special web site was prepared for the Kalamazoo Watershed project to assist them in prioritizing and developing a watershed management strategy. A substantial effort has been completed using all the digital orthoquads (DOQQ) available across Michigan. These have been acquired and seamlessly integrated with quality control and compression algorithms. This information now serves as a backdrop on our "Know Your Watershed" web site. The DOQQ integrated data set is also used as a backdrop for soils information on IWRs new EZMapper web site. This site was specifically designed to aid with Comprehensive Nutrient Management Plan development for agricultural farms throughout the state. The system allows downloading of software to outline fields and utilize the available data. Recently, automatic extraction procedures were added to Digital Watershed to incorporate DOQQ's imagery on the fly across the U.S. from Microsoft Terra Server.

IWR, Purdue University, and EPA Region 5 organized a workshop that examined web-based tools for land use and watershed planning. The Mapper is now under way to serve-up these tools across all states within Region 5, along with obtaining the same data that would be common for each state.

What is the Midwest Partnership for Watershed Management Decision Support Systems?
In April 2002.US EPA Region 5, Michigan State University, and Purdue University co-hosted the Midwest Web-based Spatial Workshop in Chicago.
Various decision support and GIS systems were demonstrated, and experiences and "wisdom" learned were shared amongst practitioners. In attendance were:

- State, Federal, and Tribal water resource managers
- Land Grant University Extension community
- Watershed managers and local government representatives

The goal of the Midwest Partnership for Watershed Management Decision Support Systems is to develop, promote, and disseminate web-based spatial decision support systems to help manage watersheds in the Midwest.

One outcome of the workshop was a commitment by the participants to advance Region-wide web-based decision support efforts for watershed management. The Midwest Partnership for Watershed Management Spatial Decision Support Systems is another outcome of the workshop. *(More about the Workshop, its objectives, and attendees).*

Local watershed management forms the basis for continued economic development and environmental improvement in the United States. Success depends on an integrated approach that brings together scientific, education and training advances made across many individual disciplines and modified to fit the needs of the individuals and groups, who must write, implement, evaluate, and adjust their watershed management plans. The purpose of our 5-year project is to:

- Improve the management of watersheds in Region 5 through the development, promotion and use of a web-based, user-friendly, geo-spatial watershed management data and decision support system (WMDDSS).
- Help set the standard for other watershed management programs across the country.

The partnership includes:

- Indiana Department of Environmental Management
- International City/County Management Association
- Michigan State University, Institute of Water Research
- Purdue University - Agricultural and Biological Engineering, Forestry and Natural Resources
- State University of New York at Buffalo
- University of Wisconsin Extension
- U.S. Environmental Protection Agency, Region 5 - Office of Public Affairs, Water Division and the Office of Information Services
- Wisconsin Department of Natural Resources

New and Future Development for Digital Watershed

As a key technical component of Midwest Spatial Decision Support System Partnership, the Institute of Water Research's Digital Watershed (DW) website has been recognized by EPA Office of Research and Development as an important environmental computing portal for a suite of EPA's environmental decision support tools. Funding is underway to support the future development of DW to achieve this goal. The first step is to integrate EPA's ATtILA (Analytical Tools Interface for Landscape Assessments) tool into DW and provide watershed comparison function at 8-digit watershed level. This work will lay a solid foundation for the integration of other EPA decision support tools such as Regional Vulnerability Assessment Program's EDT (Environmental Decision Toolkit).

The Institute of Water Research was also awarded a grant by the US Army Corps of Engineers Chicago District to create a tool that integrates a GIS-based sediment runoff predictive tool, MUSLE (Modified Universal Soil Loss Equation), into Digital Watershed (DW) and the Long-Term Hydrologic Impact Assessment (L-THIA) system and its associated EQIP tools. The resulting modeling and decision support tool will be easily accessed and used by a wide variety of expertise levels in determining the effects of development and different agricultural practices to the sediment loadings within two tributaries to Lake Michigan in Northwest Indiana; Burns Ditch/Little Calumet East Branch and Trail Creek. We've recently completed EQIP and the preliminary MUSLE integration on the project. In the near future, users will be able to model different BMP scenarios using this online tool.

Another new function that's already up and operational on Digital Watershed is the Google Map and Google Earth interoperability capability. Users can explore their own watersheds on Google Maps or Google Earth by simply click a button on Digital Watershed interface. We've received a lot of positive feedbacks on this new development.

The web-available Mapping is used extensively in IWRs Virtual Watershed Management courses. This past year we offered all four 3-credit modules of Watershed Management each semester in the series for Certification. There are now over 120 students registered per year in these courses.

Our work with the Michigan Department of Environmental Quality (DEQ) continues at a high level. With funding, between $700,000 and $1M dollars per year, it is largely the result of the Institutes' responsibilities being recognized statewide. This cooperation has led to a major role coordinated by the USGS Michigan Water Science Center and IWR; details follow. The U.S. Geological Survey (USGS) and Michigan State University (MSU) are leading a cooperative effort to assist Michigan Department of Environmental Quality (MDEQ) in meeting the requirements of Section 32802 of Public Act 148. Interim products, task-specific work plans, appropriate review and comment periods, and quarterly project meetings, or a t more frequent intervals, as requested by MDEQ or necessitated by project accomplishments.

The project activities are organized according to the parts of Section 32802. All project activities described below will be part of a team effort including MDEQ, USGS, and MSU. All activities, however, have an identified lead or co-lead role. Product completion dates, as well as timeframes for completing sub-activities necessary to meet completion dates, are identified. Also included is $1,150,000. MDEQ funds of $900,000 will be split equally between USGS and MSU. USGS Cooperative Water Program funds of $250,000 will be added to the USGS component of the project.

(a) Location and water yielding capabilities of aquifers in the state
(b) Aquifer recharge rates in the state
(c) Static water levels of groundwater in the state
(d) Base flow of rivers and streams in the state
(e) Conflict areas in the state
(f) Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources, that are identified on the natural features inventory
(g) The location and pumping capacity of all of the following: (i) industrial or processing facilities registered under section 32705 that withdraw groundwater, (ii) irrigation facilities registered under section 32705 that withdraw groundwater, (iii) public water supply systems that have the capacity to withdraw over 100,000 gallons of groundwater per day average in any consecutive 30-day period
(h) Aggregate agricultural water use and consumptive use, by township

Our strategic plan for the Michigan Institute of Water Research (IWR) over the next five years has been developed and submitted to the Director of the Michigan Agricultural Experiment Station, the Dean of the College of Agriculture and Natural Resources at Michigan State University (CANR-MSU), and subsequently to the Office of the Vice President for Research and Development. The strategic plan outlines a number of key strengthening components for the MI IWR. (1) The affiliate positions within the Institute. These positions might be 25% time in the IWR and 75% in a discipline department. A group of affiliates would greatly strengthen the discourse relative to problems and techniques for solving them as well as the information dissemination. Additionally, adjunct faculty are generally somewhat less involved but enhanced mutual awareness of our programs would greatly enrich the pool of expertise of water scientists from which we could draw upon in order to more effectively address issues of concern within IWR. (2) Enhanced funding for the IWR: New Fiscal Support: Facilitating a competitive grants program in the water arena has been proposed. Preliminary discussions relative to the plan are leading to the strong possibility of adjunct and joint affiliate positions, but any new funding is on hold in light of the State's budget difficulties.

Related Research

We continue to obtain synergistic impacts by closely aligning our efforts with support from such organizations as the Corps of Engineers, USDA, US Forest Service and numerous other agencies and NGO's. This past year we received a grant from the Corps of Engineers for $75,000 which involves estimating sediment delivery from each of the eight-digit watersheds within the entire U.S. side of the Great Lakes Basin. This database is not only of value to the Corps in prioritizing their efforts but also provides us with a broad set of additional information that we can use in other programs, and for assisting with the prioritization of high risk areas for erosion throughout the region. USDA funds involve a coordinating effort of outreach and research among all states within the EPA Region V. IWR personnel are partially funded through this regional project which coordinates and facilitates the communication of research methodologies, approaches, and results from our research and aides with region-wide outreach programming.

Training Potential

New graduates and graduate training continue to be a high priority of IWR. Unfortunately, graduate stipends have increased to the extent that a 1/2 time graduate student with fringe benefits, requires from $35,000-$45,000 (per year). We will make every effort to continue incorporating graduate students but with the high cost, it is increasingly difficult to employ more than a few students at any given time. As part of our partnership philosophy, we have jointly supported numerous graduate students with other departments and units on campus.

Special Project

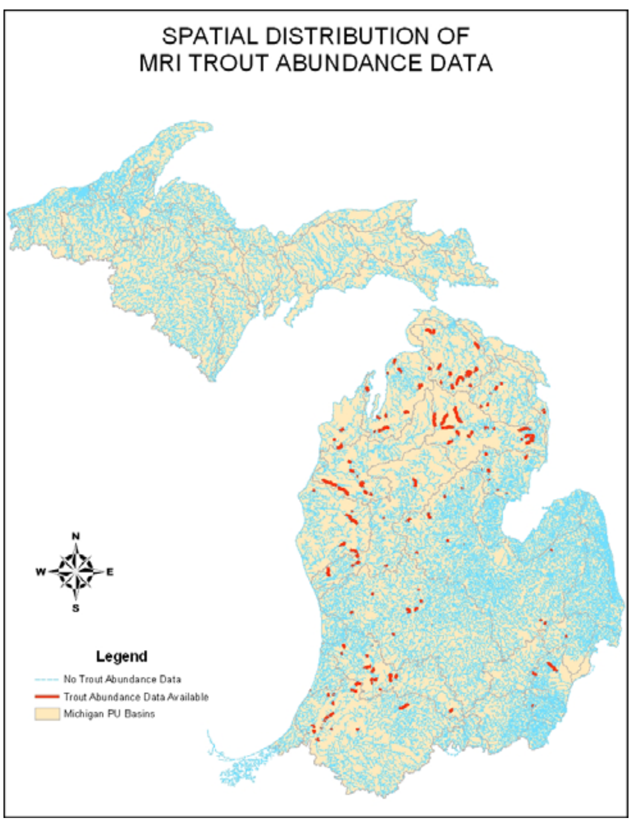
State: MI
Start: 03/01/05 (actual)
End: 02/28/06 (actual)
Title: 1.3 Ecological Modeling
Project Type: Research
Focus Categories: Water Quality, Water Quantity, Models
Research Category: Water Quality
Keywords: Ecological Modeling, Water Temperature and Flow Modeling, Fish Modeling, GIS Framework, Catchment
Principal Investigators: Lizhu Wang, M.J. Wiley and Paul Seelbach

River Fish Models

- *Fish Selection Objective:* Identification of fish species that are sensitive to water temperature and flow variations. The development of predictive models for only those identified fish species because only fishes that are sensitive to changes of temperature and flow are relevant to the GLPF objective.

- *Environmental Variables Objective:* Identification of key environmental variables most influential to fish distribution and abundance.

- *Develop species-specific models:* Explore different approaches to predict the occurrence and abundance of species. One potential method is multiple linear regression.



Fish Selection

Trout species (brown trout, brook trout, and rainbow trout) were selected as the fish species of interest in the GLPF study. The selection was due to trout's non-migratory nature, relatively narrow thermal tolerance, availability of historical abundance data, and the importance of the fishery. This selection has directed the scope of all further research.

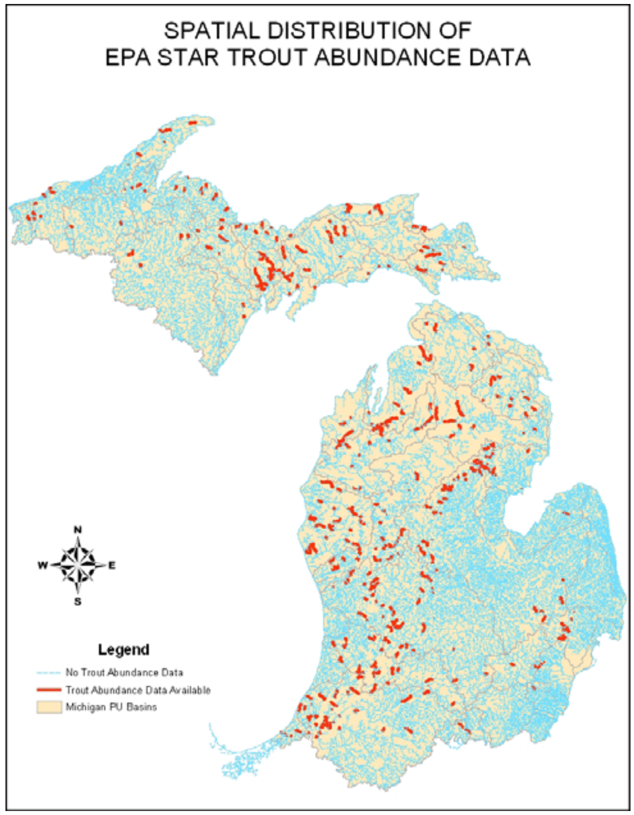
Environmental Variables

Database Creation

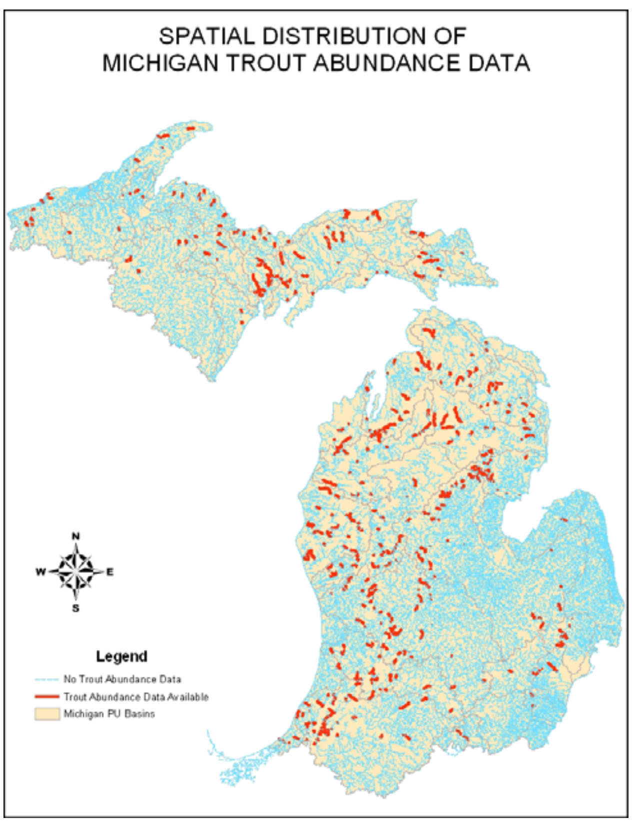
Fish community data – Fish community data from about 800 stream sites with length ranging from less than 100m to greater than 1,000m were gathered. The fish abundance data are from two data sources: Michigan

Rivers Inventory (MRI) and EPA STAR project (STAR). The MRI sites have standardized abundance estimates for 384 sites throughout Michigan, which were sampled using rotenone or multiple run electro-fishing. Because some sites were on the same inter-confluence stream reach, only 256 unique reaches were associated with modeled flow discharge and trout data (see left).

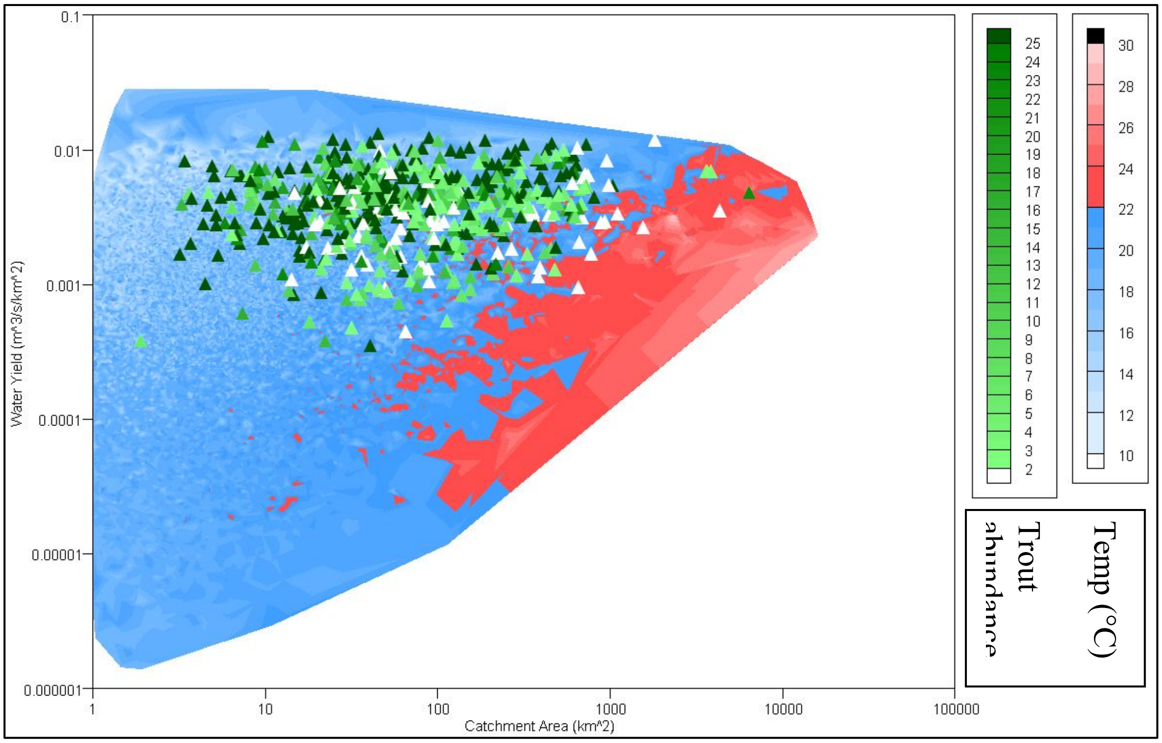
The STAR fish data consisted of 793 sites throughout Michigan. Among them, 715 sites were associated with trout data, unique reaches, and modeled discharges (see right). The majority of these sites were sampled using single-pass electro-fishing. In order to combine fish abundance values to create a larger database, it was necessary to standardize the abundance data between the MRI and STAR databases.



As this study focused on trout populations, stream reaches with trout abundance data were selected, providing 547 sites for analysis (see below). Abundance data for brown trout, brook trout, and rainbow trout were grouped together to increase the power of analyses. Additionally, previous cluster analysis work by Zorn *et al* (2002) showed a close clustering of these trout species into two overlapping fish guilds along the axes of water yield and watershed area.



The best fit transformation was using a linear regression between the MRI and STAR databases after standardizing the unit of measurement to the number of individual fish caught per 100 meters of sampling stream length. The more standard unit of fish individuals per square meter was not possible to calculate, since many sites lacked sampling width measurement. A slightly stronger regression-based transformation would have been possible by standardizing each site from the STAR and MRI databases based on deviations from standard normal, and creating a set of unitless measures. However, the results of such a transformation was deemed to be less useful in providing a metric of potential trout abundance.



Development of Fish-Flow-Thermal Model – The assessment of trout abundance based on temperature, water yield, and drainage area confirmed that trout were confined to the streams with high yields, usually smaller- to mid-sized streams, and relatively low July temperatures (see above).

The initial multiple linear regression model linking water yield, drainage area, water temperature, and trout abundance was not sensitive to relatively small base flow changes in stream reaches with large catchment areas, or regions with initially high values of water yield due to log transformations issues; a proposed decrease in discharge in a river with a high water yield due to regional pumping would appear to cause little change in temperature, and therefore little impact to trout.

The initial assessment of trout abundance and temperature did not show a strong relationship, since the use of mean July water temperature did not assess the daily temperature stability of any particular site. It was felt that the inclusion of temperature stability would increase the predictive capability of trout abundances, especially at their upper thermal tolerance limits.

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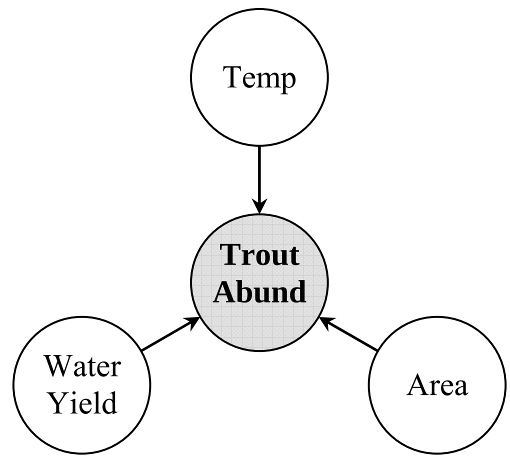
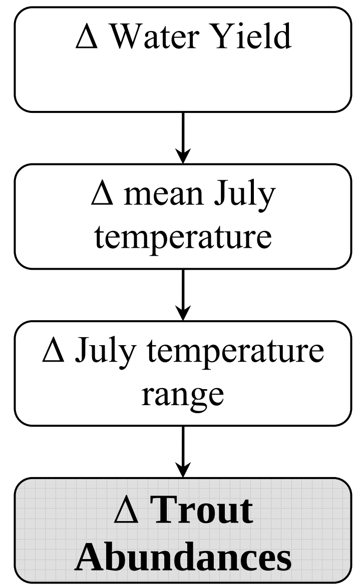
To try and ascertain daily temperature stability, additional work explored the possibility of dividing the original single model into a series of three consecutive models (see below). The first model was intended to predict changes in July mean water temperature based primarily on changes in water discharge. The second model would predict temperature stability also based on changes in discharge. The third model would predict trout abundances based on the altered temperature stability and July mean temperatures. It was our hope that these statistical models would incorporate additional climate and landcover parameters and could be used to



Original model theoretical framework.



Three-stage model theoretical framework.

quantitatively describe the temperature changes resulted from base flow changes from either ground water withdrawals or BMPs.

Stream Temperature Collection and Analysis – In order to start an assessment of temperature stability, records of July temperatures from a total of 556 temperature sites were obtained from Michigan's Fish Collection System and from regional DNR biologists. The data had been minimally collected for one year, although some sites had up to three-year's of data. The overall dataset spanned the summers from 1993 to 2005. These temperature data were quality-checked and summarized into daily means, minimums, and maximums for the period when the data were collected. All the temperature data sites have been linked to the stream reaches where stream base-flow yield and other landscape variables were predicted or gathered using GIS tools. Summer temperature means and temperature fluctuation means were calculated for each site. Modeled mean July temperatures for all Michigan stream reaches were used where no measured temperatures were available.

Prediction of Mean Temperature Changes – Because water temperatures are strongly influenced by water yield, we have attempted to predict the mean July temperature based on the water yield and other related variables. A linear regression model based on changes in yield within the 539 trout streams with available abundance data were used to examine the amount of temperature change expected due to changes in water yield. The model produced was not in satisfactory form to meet our objective. We are continuing the process of improving the predictive capability of this model.

Prediction of Mean Daily Temperature Stability – Because trout presence and abundance are not only determined by mean water temperature, but also determined by temperature variation, we attempted to develop a model that could be used to predict daily temperature ranges. A multiple linear regression model based on parameters of modeled temperature, watershed area, and stream segment slope regressed against 216 summarized measured temperature ranges was used to create a set of modeled mean daily temperature ranges.

Modeled daily temperature ranges were not significantly different from the observed daily temperature ranges. Using this initial set of modeled temperature ranges, another regression was done to estimate the magnitude of the changes in temperature range due to expected changes in discharge within the 539 trout streams used in the previous section. We are continuing the process of improving the predictive capability of this model.

One current concern is the positive correlative relationship between increasing daily temperature range and trout abundance. Several different methods of statistically isolating the upper bound thermal preferences in trout are being explored, since the inclusion of temperature stability was due initially to a concern of temperature preferences in streams with trout-marginal temperatures.

Application of Multiple Linear Regression Model

Using an expected value of a 1.5 cfs decrease in stream discharge due to regional groundwater pumping provided from the surface and groundwater modeling teams, the changes in temperature and temperature range were modeled using the methods outlined above. The changes in mean temperature and daily temperature ranges were added to the base modeled values. Increases in mean daily temperature and daily temperature ranges were found to be slightly, although not significantly, increased due to pumping.

Using the modeled temperature changes, a first estimate of expected maximum trout abundance was created based on changes in modeled temperature using linear regression. Inclusion of the temperature flux variable did not work as expected, and was been excluded. In all areas, maximum expected trout abundance had decreased slightly, but not significantly based on the current power of the model. We are continuing to increase the predictive capability of this model.

Reference

Zorn, T., P.W. Seelbach, and M.J. Wiley 2002. “Distributions of Stream Fishes and their Relationship to Stream Size and Hydrology in Michigan’s Lower Peninsula.” *Transactions of the American Fisheries Society* 131: 70-85

Evaluation of Low-Disturbance Tillage in Mitigating the Transport of Bacterial Contaminants from Land Applied Dairy Slurry to Subsurface Drains

Basic Information

Title:	Evaluation of Low-Disturbance Tillage in Mitigating the Transport of Bacterial Contaminants from Land Applied Dairy Slurry to Subsurface Drains
Project Number:	2005MI60B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	8th
Research Category:	Engineering
Focus Category:	Agriculture, Water Quality, None
Descriptors:	Subsurface drainage, tile line, manure management, bacteria, pathogens, cover crop.
Principal Investigators:	Timothy M. Harrigan

Publication

Project Number: 2005MI60B
Start: 03/01/05 (actual)
End: 02/28/06 (actual)
Reporting period: 1/1/05 to 6/30/06
Title: Evaluation of low-disturbance tillage in mitigating transport of bacterial contaminants from land applied dairy manure to subsurface drains.
Investigators: Timothy M. Harrigan, Biosystems and Agricultural Engineering, Michigan State University
Focus Categories: Agriculture, Water Quality
Congressional District: eighth
Descriptors: Subsurface drainage, tile line, manure management, bacteria, pathogens, cover crop.

Abstract

Twelve instrumented flumes with sampling ports were installed in subsurface drains at a three hectare site in a Blount loam soil on a dairy farm in the Raisin watershed in Lenawee County, Michigan. A low-disturbance rolling-tine aerator and a subsurface manure slurry deposition system were used to apply liquid dairy manure in large replicated plots (no manure, manure, and manure plus desiccated cereal rye cover crop) 56000 L/ha. Drainage effluent was sampled and analyzed for total fecal coliforms and E. coli before manure application, two hours after application, two days and 16 days after application. The site received 24 mm of precipitation between manure application on May 1 and the two-day sampling event on May 3, and an additional 53 mm between May 10 and May 16. No fecal coliforms or E. coli were detected in pre-application samples. Two hours after manure application a low level of fecal coliforms and E. coli (<10 C.F.U. per 100 ml) were detected in effluent from manured treatments.

Objectives

The overall goal was to develop guidelines for environmentally sensitive application of livestock slurry on artificially drainage farm land. Specific objectives were to evaluate the bacteriological water quality of:

- Spring manure slurry deposition over aeration tillage slots in a no-till cropping system.
- Spring manure slurry deposition over aeration tillage slots and a desiccated, fall-planted cereal rye cover crop in no-till ground.

Methods and procedures

Twelve circular flumes with water sampling ports were installed in subsurface drains at a 3 ha site in a predominately Blount loam soil (*Fine, illitic, mesic Aeric Epiaqualfs*) in Lenawee County, Michigan (42.16º N, 81.06º W) in a long-term, no-till corn/corn silage/soybean cropping system. The subsurface drains (20 cm diameter, 15 m spacing, 0.9 m depth) were installed in 1995. A cereal rye (var. Wheeler, 125 kg/ha) cover crop was direct-drilled in a 9.8 m wide swaths centered in portions of the field on October 10, 2005. On April 14, 2006 the cereal rye cover crop (approx. 15 cm top growth) was sprayed with glyphosate (1.8 L/ha A.I.) to facilitate planting of soybeans in early May.

All treatments were pre-tilled with a rolling-tine aerator (3.66 m; Aer-Way, Holland

Equipment Ltd. Norwich, Ontario, Canada)[1] prior to manure application. The aerator was rear-mounted on a commercially available slurry tanker (11,340 L; Husky Mfg., Alma, Ontario, Canada) and was equipped with a SSD (sub-surface deposition, Holland Equipment Ltd. Norwich, Ontario, Canada) slurry distribution system (Fig. 1). The angle of the tillage tool shaft was set at 2.5º to fracture the soil yet minimize surface roughness at planting. No additional seedbed tillage or soil firming was done.

Figure 1. The manure slurry was applied at 56,000 L/ha following aeration tillage to loosen the soil and improve infiltration.

The aeration tillage tool and slurry tank were drawn behind a 112 kW tractor at 4.8 km h^{-1}. The manure slurry (56,000 L/ha) passed through a chopper/distributor (300 RPM) with radially configured outlets and was placed over the aeration slots in the fractured and loosened soil behind each set of rolling tines.

Samples of the drain effluent were drawn from each of the sampling wells on May 1 (prior to manure application and again two hours after application), May 3, and on May 16. The samples (125 ml) were drawn with a peristaltic pump and stored on ice in a closed container. The sampling tube was sanitized by circulating a 10% solution of sodium hypochlorite through the tube, allowing continuous contact for 10 minutes and double rinsing. All samples were processed within 24 h.

Water samples were analyzed using standard membrane-filtration methods (APHA, 1998) for detection of fecal coliform (FC) bacteria (mFC medium, Difco, Detroit, MI) and *Escherichia coli* (NA-MUG medium, Difco). All media was prepared according to manufacturer's instructions. For each water sample 50, 5 and 0.5 mL volumes were filtered though a 0.45 micron nylon membrane filter that was transferred to mFC medium and incubated at 44.5 ºC for 24 hr. If growth was uncountable at these dilutions further 10-fold serial dilutions were made to obtain countable growth. Bacteria enumeration was based on preparations with between 20-80 colonies, or calculated from multiple dilutions in the case of non-ideal counts. Following enumeration of FC colonies, the filter with the appropriate range of colonies was transferred to NA-MUG medium and incubated at 37 ºC for 4 hr. Fluorescent colonies were counted as *Escherichia coli*.

Statistical Analysis

The experiment was a randomized complete block design with four replications and three treatments (no manure, manure, and manure over a desiccated cereal rye cover crop). The null hypothesis of no difference in the median values of the bacteriological water quality of the drain effluent among treatments was tested with $\alpha = 0.05$ using the Friedman test in XLSTAT 2006 statistical software (Microsoft Corp., 2006). Multiple comparisons between the levels of factors to obtain significant differences for all pair-wise differences were conducted using Dunn's procedure (Dunn, 1964).

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[1] Mention of trade names, proprietary products, or specific equipment is intended for reader information only and constitutes neither a guarantee nor warranty by Michigan State University, nor does it imply approval of the product named to the exclusion of other products.

Results and discussion

No *E. coli* or fecal coliform bacteria were detected in the pre-application water samples. Low levels (≤ 1 cfu/ml) were detected in the manure-applied and control treatments two hours after sampling, but concentrations were below Michigan standards for full body contact. The May 3 samples were drawn following 23 mm rainfall in the previous 24 h (Fig. 2). Low levels of *E. coli* and fecal coliforms were detected in two of the control treatments indicating either a hydraulic connection between the no-manure control and one of the manure treatments, or contamination of the control from natural sources. Although the treatments receiving aeration tillage plus manure tended to have greater levels of *E. coli* and fecal coliforms, the manure treatment was not significantly different from the control. The manure on a desiccated cereal rye cover crop was significantly greater than the no-manure control ($p \leq 0.039$).

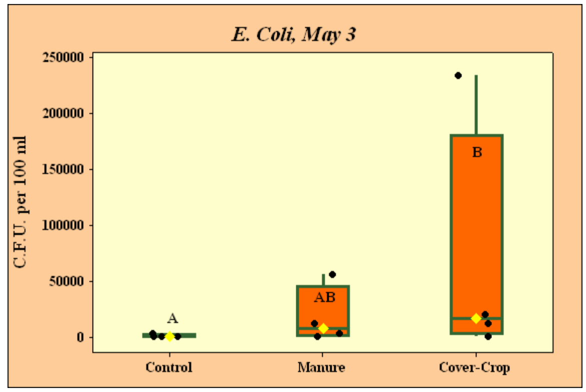


Figure 2. The E. coli concentration in the manure plus desiccated cover crop treatment was significantly greater than the no-manure control two days after manure application.

The microbiological quality of the May 16 samples indicated less than one cfu/100 ml *E. coli* in all treatments (Fig. 3). However, both manure application treatments were significantly greater than the no-manure control ($p \leq 0.039$).

Conclusions

- When aeration tillage preceded a controlled manure slurry application rate of 56,000 L/ha in no-till crop land in the spring prior to planting, the microbiological quality of the subsurface drain effluent did not exceed the Michigan standard for full body contact two hours after spreading.
- Manure slurry application with aeration tillage over a desiccated cereal rye cover crop lead to a statistically significant increase in E. coli and fecal coliform concentration in the subsurface drain effluent compared to the no-manure control.

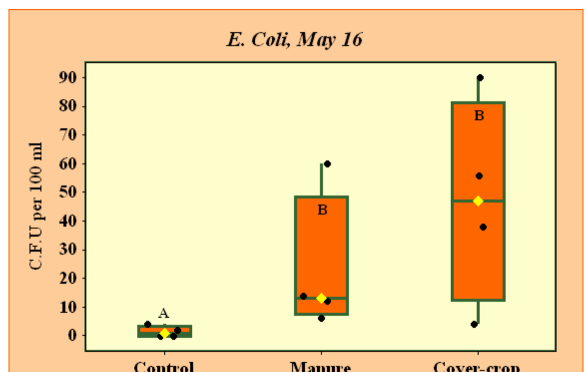


Figure 3. Although the E. coli concentration for all treatments were below the standard for full body contact, both manure-applied treatments were significantly greater than the no-manure control.

Grant No. 05HQGR0170 Integrating ACOE Sediment Runoff Predictive Tool into DW-L-THIA System

Basic Information

Title:	Grant No. 05HQGR0170 Integrating ACOE Sediment Runoff Predictive Tool into DW-L-THIA System
Project Number:	2005MI96S
Start Date:	9/1/2005
End Date:	8/31/2006
Funding Source:	Supplemental
Congressional District:	8th
Research Category:	Water Quality
Focus Category:	Water Quality, Sediments, Models
Descriptors:	Spatial Decision Support Systems
Principal Investigators:	Yi Shi, Jon Bartholic, Bernard Engel

Publication

Grant Number: 05HQGR0170
Start: 09/01/05 (actual)
End: 08/31/06 (expected)
Title: Sediment runoff predictive tool using the DW-L-THIA system Project Progress
Investigators: Yi Shi, Jon F. Bartholic, Institute of Water Research, Michigan State University and Bernard Engel, Purdue University
Focus Categories: Water Quality, Sediments, Models
Congressional District: eighth
Descriptors: Decision Spatial Support System

The goal of this project is to create a tool for the Army Corps of Engineers (ACOE) Chicago District that integrates a GIS-based sediment runoff predictive tool into Digital Watershed (DW) and the Long-Term Hydrologic Impact Assessment (L-THIA) system and its associated tools so the resulting modeling and decision support tool can be easily accessed and used by a wide variety of expertise levels in determining the effects of development and different agricultural practices to the sediment loadings within two tributaries to Lake Michigan in Northwest Indiana; Burns Ditch/Little Calumet East Branch and Trail Creek.

The model we selected to integrate is MUSLE, Modified Universal Soil Loss Equation. Currently we have done data collection and pre-processing works.
We've also conducted SEDMOD/RUSLE modeling for the two watersheds and made the results available online at Digital Watershed website. The stakeholder workshop was held successfully last November. The EQIP and Digital Watershed have been linked together as defined in project task 2. Now we are in the process of completing task 3, MUSLE integration. The preliminary integration has been done so users can conduct MUSLE modeling for a user delineated watershed on the fly. The further work will be done in the near future so users can model different BMP scenarios.

Grant No. 05HQGR0172 Strategic Conceptual Plan for Submittal to the Army Corps of Engineers for the 516(e) Great Lakes Tributary Modeling Program

Basic Information

Title:	Grant No. 05HQGR0172 Strategic Conceptual Plan for Submittal to the Army Corps of Engineers for the 516(e) Great Lakes Tributary Modeling Program
Project Number:	2005MI97S
Start Date:	9/1/2005
End Date:	8/31/2009
Funding Source:	Supplemental
Congressional District:	8th
Research Category:	Water Quality
Focus Category:	Water Quality, Sediments, Models
Descriptors:	Spatial Decision Support System
Principal Investigators:	Jon Bartholic, Jeremiah A Asher, Ouyang Da, Da Ouyang, Saichon Seedang, Yi Shi

Publication

Grant Number: 05HQGR0172
Start: 09/01/05 (actual)
End: 08/31/09 (expected)
Title: Strategic Conceptual Plan for Submittal to The Army Corps of Engineers for the 516(e) Great Lakes Tributary Modeling Program
Investigators: **J**on Bartholic, Yi Shi, Saichon Seedang, Da Ouyang, and Jeremiah Asher, Institute of Water Research, Michigan State University
Focus Categories: Water Quality, Sediments, Models
Congressional District: eighth
Descriptors: Decision Spatial Support System

Purpose

Our purpose is to conduct a more detailed study on soil erosion and sedimentation, and utilizing new web-based information technology capabilities that use spatial data and models, plus economic and policy perspectives for more effective support of state and local efforts to reduce sediment and pollutant loadings to tributaries in the Great Lakes Basin. The ACOE Great Lakes Tributary Modeling Program can generally be considered at the mid-point of its effort to economically reduce sedimentation in the Great Lakes Basin. This project initiates the building process for a scalable, long-term public website system. This system will incorporate much of the web-based and stand-alone tools developed to-date with emphasis on general delivery available under the Digital Watershed web system. In addition, there will be new modules developed for the system over the next several years. Other key features include, a live help desk/hotline to answer questions and provide technical assistance relative to the system and the continual application of new approaches to minimize soil loss and sedimentation. The combined results of previous and future planned efforts wrapped into a long-term public website will be the essence of a sustainable support system for the continual minimization of sedimentation to our rivers, ports and lakes. The first tasks to be undertaken are provided in detail under "Proposed Work for FY05".

Problem/Demand

Sediment and nutrient loadings from nonpoint sources are major contributors to water pollution in the Great Lakes region and throughout the world. Sediment loadings cause two highly adverse economic impacts on our ecosystem: 1) lost productivity from unnecessary erosion and 2) the costs of dredging for navigational and environmental purposes. The U.S. Army Corps of Engineers (ACOE) Detroit District office alone expends over $6 million annually for dredging sediment from Great Lakes waterways within their jurisdiction. To control and reduce these loadings to our rivers, lakes, and streams, public agencies and private land owners need effective tools for targeting practices that reduce the volume of sediment leaving the land.

As a result of its diffuse and pervasive nature, reducing nonpoint source pollution requires the collaborative efforts of several federal agencies including the U.S. Environmental Protection Agency (EPA), the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS), and the ACOE. According to the EPA, approximately 40% of water bodies in the U.S. fail to meet clean water standards. Consequently, the EPA is currently engaged in a process to establish total maximum daily loads (TMDLs) for sediment and nutrient loadings for these water bodies. Under the Clean Water Act Section 319 Nonpoint Source National

Monitoring Program and wetland protection programs, the EPA funds and programs support efforts to reduce the negative impacts of runoff from agricultural, urban, and industrialized areas. Similarly, the NRCS has been provided with millions in federal funds to support agricultural best management practices (BMPs) in an effort to reduce the movement of pollutants into our waterways.

The ACOE Great Lakes Tributary Modeling Program, under Section 516(e) of the Water Resources Development Act of 1996, is an important initiative, which complements other programs designed to reduce sediment delivery to rivers and streams. This Program has funded numerous modeling efforts intended to encourage watershed planning and other local actions to control sediment movement and impacts. However, to achieve optimal reduction of pollutant loadings in water quality-impaired watersheds and to maintain water quality in others, there is an increasing demand for tools that provide accurate assessment of best conservation practices to apply and prioritize risk prone sites in these watersheds.

New Capacity and Opportunities

The following elements provide important new capacity that applies IT (information technology) systems to the protection of our water resources from adverse impacts of nonpoint source pollution:

- Spatial databases and GIS spatial analysis functions,
- Broader bandwidth on the Internet with wide WebGIS and spatial data availability,
- Spatial hydrologic models including best management practices (BMP) optimization,
- Data sharing standards/protocols, and
- User-friendly interfaces and online education programs.

With advances in distributed computing, online real time environmental modeling functions can now be implemented. Immediate educational training for web users can also be provided with web-based educational modules. The benefits of web-accessible information and ease of use through web-accessible educational training will bring valuable information into the decision making process as well as promote the widest possible application of the tool and its functions. A truly distributed system that can access data and functions from other online servers can be built.

Spatial Hydrologic Models

Computer modeling is generally regarded as an academic and public policy research tool. However, if modeling and GIS/screening tools cannot be developed for use by the people who need them most, then the value of these tools is greatly diminished. Formidable barriers to the application of scientifically-robust hydrologic and water quality models have precluded their wider use. Field personnel (e.g. district conservationists, watershed groups, extension staff, etc.) frequently find the volume of data and level of technical expertise needed to use hydrologic and water quality models overwhelming. The objective of this effort is to remove these barriers by developing a robust, scientifically-sound, watershed scale erosion and sedimentation assessment system that can be easily used by planners and field personnel.

These web-based tools will be designed for use by field personnel and local stakeholders at both the field and watershed scales to identify critical erosion-prone areas and to evaluate the effectiveness of alternative management practices that reduce erosion and sediment transport. Pollution reduction from specific sites can be aggregated across each watershed to determine their cumulative effects. By utilizing web-based tools, practices deployed within a watershed can be monitored, and their impacts on reducing sediment can be aggregated for each watershed to evaluate the cumulative potential reduction and sediment movement to the stream over time. The end result will be a web-accessible, fully-developed spatial analysis tool to target high-risk areas and optimal BMP selection for greater reductions of sediment reaching our water bodies. This integrated spatial analysis tool and process will be easily adapted to other regions.

Building on Existing Efforts

The ACOE Great Lakes Tributary Modeling Program has supported the development of sediment transport models for tributaries to strengthen the effectiveness of state, region, and local entities in reducing sediment loads. Substantial progress has been made to achieve these Program objectives. As new spatial analysis tools are developed, these tools can be brought on-line for broader use and accessed via the web for use in future tributary modeling.

Similar GIS-based watershed mapping tools have been developed by IWR-MSU. These tools include Understanding Your Watershed (http://www.iwr.msu.edu/water/), Digital Watershed (http://www.iwr.msu.edu/dw/), and Online RUSLE (http://www.iwr.msu.edu/rusle/). In addition, IWR has a project with Purdue University to jointly integrate their web capabilities and ours into an integrated web system. This effort “The Midwest Spatial Decision Support System Partnership” is supported by EPA Region 5. Locally a “system” could assist managers in managing multiple environmental problems simultaneously by having this Army Corp of Engineers effort developed synergistically with the Midwest Spatial Decision Support System Partner. The Corp effort will be an integrated part of the SDSS as it also continues to evolve.

Technology transfer remains a critical component for broad stakeholder use. To facilitate this critical technology transfer, a user-friendly interface will be designed with interactive menus and help tools. Users will be able to provide minimal data inputs to assess the potential impacts of alternative management practices (BMPs) that reduce sediment loads. Immediate educational training for web users can also be provided with web-based educational modules. The immediate benefits of web-accessible information and ease of use through web-accessible educational training will bring valuable information into the decision making process as well as promote the widest possible application of the tool and its functions.

Proposed Work for FY05

The IWR study completed in 2003 provided “big picture” scenarios in analyzing comparative loading and ranking of estimated soil erosion and sediment loads by 8-digit watersheds in the Great Lakes Basin. Data used in the previous study were obtained from EPA’s BASINS for the 8-digit watersheds. For the work of FY04, we used a finer resolution digital elevation model (DEM) along with residue management survey data from Conservation Technology Information

Center (CTIC). This allowed us to initiate more detailed analysis on the effects of Best Management Practices (BMPs) on erosion and sediment in a test watershed. In addition, a web-based application provided a spatial tool for identifying specific potential contributing areas.

Work for Year One includes four components (tasks).

The first step (Task 1) is to develop and empower the advisory input and feedback process to aid in the direction and evolution of the long-term sediment reduction public web site development. The make up of the advisory input will be diverse and incorporate both those interested in sediment reduction programs and those involved in putting practices on the land to reduce soil loss to or in our waterways. The advisory process will include for example the Michigan Association of Conservation Districts through the executive director Marilyn Shy, the districts Great Lakes designate Tom Middleton, representatives from NRCS and their RC and D's, Farm Bureau, MDA, DEQ, the Nature Conservancy, plus the First Nation and end users including farmers, township officials and watershed representatives. One representative from each of the three Corp districts will also be part of the advisory process. This group will meet quarterly initially and then semi-annually as the effort unfolds. Their responsibility will not only be to guide the development and evolution of the effort but they will also provide a conduit for extending the capabilities and knowledge about the website to their own particular segments of the land management community.

The second step (Task 2) is to develop and use simple screening tools to locate potential (vulnerable) sediment contributing areas in an entire watershed or any sub watershed. These tools will be based on river curvature, slope, and an extensive spatial database including soil, land cover and additional layers. River curvature can be calculated and utilized to locate most vulnerable stream segments for bank erosion. Slope, soil, and land cover can be overlaid together to find high-risk areas for sedimentation from land surface in a watershed. A 3D visualization tool combined with a 2D web-based mapping tool can also aid users in this first step screening process. The goal of this process is to help develop the most effective holistic plan for reducing sediment from the entire watershed systems.

The third step (Task 3) is to develop and use watershed-based sediment modeling tools to conduct detailed studies on the high risk areas spotted in Task 2. Advanced watershed models using SEDMOD and RUSLE will be used in this step. Specifically, baselines of soil erosion and sediments in the Great Lakes Basin can be determined utilizing CTIC residue management surveys which provide data on management practices such as reduced tillage and no till for various crops on a county basis. CTIC data will be used with the finer resolution $30m^2$ DEM data from the U.S. Geological Survey; the CTIC data will help us to refine our previous study. Our prior study showed that sediment loading varied greatly and is a function of tillage practices. The results will help ACOE and other organizations such as National Association of Conservation Districts (NACD) to determine the baselines in order to set their erosion/sediment reduction goals.

Various economic incentive programs for adopting the BMPs for sediment/erosion reduction will also be incorporated into the goals. In the process we will capture data on sediment loss potential (risk) for every $30m^2$ cell. We will test the system on four different 8-digit watersheds.

The fourth step (Task 4) Even though the use of BMP's on highly erodible land is the most widely utilized method for reducing sediment, an entirely new policy approach such as master planning, zoning, building permits, set-back, etc. will be extensively investigated. Economic information from landowners, in response to these new policies, will be reviewed. We expect that a rich set of policy, planning, and permitting "tools" that utilize the sediment risk maps and optimize analysis being developed, will provide new key options for protecting high risk areas from inappropriate development. The approaches used in managing development within the mapped flood plain will provide a starting reference for ideas (policy tools) that can also be used with sediment risk maps.

Timeline

We anticipate that the proposed work in Tasks 1 through 4 will be completed in 10 months. Task 1 will be undertaken immediately so input and feedback can be incorporated as this effort proceeds and detailed plans for out years evolve. A year-one project report and papers will be written during the last two months.

Follow-on activities to develop the sediment risk public website

In year two we will 1) develop more detailed BMP's 2) generate sediment loss potential (risk) for every $30m^2$ cell on the U.S. side of the basin using tested and evaluated methodology from year 1.. These spatial files will then be entered into Digital Watershed so detailed erosion maps can be accessed and utilized. We will develop, evaluate and use methodology for assessing and displaying 8-digit and the 12-digit watersheds within potential sediment risk maps. This methodology and web mapping technique will be evaluated for usefulness through the advisory input and feedback process developed in Task 1 (Year 1). Then the revised/improved approach will be automated for use in the 2nd year to generate the layers and their basin wide integration into Digital Watershed. 3) Initiate the implementation of policy findings originating in year one. These include the policy for erosion/sediment reduction on various activities in the watershed areas and economic incentive consideration for farmers to adopt various BMPs. 4) We will initiate certain aspects of the help task and support for those using the tools already in existence. Special programs would be added to the web based interface so that users can develop various scenarios for the implementation of BMP's by sectors (Agriculture, Urban and Forestry) to allow them to maximize the cost/benefit from their sediment reduction efforts.

In the third year the scenario tool would be further developed including assistance for meeting TMDL's and/or sediment reduction goals. Some optimization would be incorporated to aid in the generation of best scenarios for sediment reduction. Further, there will be broader technical assistance; the help desk will be expanded along with a set of frequently asked questions. Additionally, because of the great potential for policy developments at the local level including ordinances etc., to reduce high-risk activities impacting sediment on high erosion prone areas, a component would be developed to link local units of government that had successfully implemented local land use policies for sedimentation reduction to new units of government seeking to implement the policies in their jurisdiction.

In the fourth year, additional new tools will be developed and existing tools revised as guided and requested by the advisory input and feedback system. The optimization routine would be further expanded for ease of use and breadth of application. The help task would become fully operational. Immediate educational training for web users will also be provided with web-based educational modules. The immediate benefits of web-accessible information and ease of use through web-accessible educational training will bring valuable information into the decision making process as well as promote the widest possible application of the tool and its functions.

Grant No. 04HQGR0105 - Groundwater Inventory and Mapping Project in Support of Public Act 148

Basic Information

Title:	Grant No. 04HQGR0105 - Groundwater Inventory and Mapping Project in Support of Public Act 148
Project Number:	2005MI98S
Start Date:	3/25/2004
End Date:	9/30/2005
Funding Source:	Supplemental
Congressional District:	8th
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Education, Water Use
Descriptors:	Groundwater Mapping, GIS, Hydrogeologic Inventory
Principal Investigators:	David Lusch, Jon Bartholic, Steve Miller

Publication

Public Act 148: Groundwater Inventory and Map Project

Executive Summary

Michigan Department of Environmental Quality

August 18, 2005

Overview

Public Act 148 (Michigan, Public Acts of 2003) required the Department of Environmental Quality (DEQ) to create a "groundwater inventory and map" that includes eight specific products, a general requirement for a groundwater inventory, and a directive to make the map and inventory available to the public. The act required that the work be completed by August 8, 2005. DEQ created a cooperative research team involving groundwater and mapping experts from the U.S. Geological Survey (USGS) and Michigan State University (MSU). In a separate but related effort, Public Act 148 also created a Groundwater Conservation Advisory Council. The Council was charged to study the sustainability of groundwater resources in the State and report to the legislature by February, 2006 whether the state should provide additional oversight of groundwater withdrawals. The Council was informed of the progress of the Groundwater Inventory and Map (GWIM) Project, and the final inventory and map products have been made available to the Council to assist with the generation of their report.

Financial Support

This project was funded through a joint funding agreement between the DEQ and USGS in the amount of $900,000. The MSU team members were funded through the USGS State Water Resources Research Institute Program to the Institute of Water Research ($453,000 from the DEQ-USGS joint funding agreement). The USGS Cooperative Water Program provided additional funding for this study in the amount of $250,000. The total project budget, not including the in-kind staffing contributions from the DEQ, was $1,150,000.

In-kind staff contributions by the DEQ included oversight of the project by an engineer and geologist in the Water Bureau (WB). Extensive contributions to the project were made by WB management and other support staff. The DEQ technical advisory committee included representation from Environmental Sciences and Services, Office of Geological Survey, Remediation and Redevelopment, and Waste and Hazardous Materials divisions. The technical advisory committee met on a monthly basis. Overall, it is estimated that DEQ annual staff costs to administer this project was 2 FTEs. The extensive participation and oversight by DEQ staff resulted in many improvements and contributed to many enhancements of the products produced by the GWIM Project.

Project Team

The project team consisted of personnel from DEQ, MSU, and USGS.

Michigan Department of Environmental Quality

The team leaders were Brant Fisher and Joseph Lovato, directed by Wm. Elgar Brown. Project support was provided by Andrew LeBaron, Ronda Page and Dan

Diebolt, Source Water Protection Unit, Drinking Water and Environmental Health Section, Water Bureau. Ron Van Til, Water Use Program, provided required data for the mapping effort, as did Kristen Philip, Community Drinking Water Unit, who compiles these data for public water supplies. Chuck Thomas, Upper Peninsula District Office, provided a great deal of help on the aquifer distribution and use for the Upper Peninsula. Mike Gaber and Dave DeYoung, Well Construction Unit, provided insight on the relationship between the mapping project and the Groundwater Dispute Resolution Program, which was established by Public Act 177 (Acts of 2003).

Michigan State University

The team leaders were Dr. David Lusch (Remote Sensing & GIS Research and Outreach Services – Department of Geography, and Institute of Water Research) and Steve Miller (Department of Biosystems and Agricultural Engineering, and Institute of Water Research). Dr. Jon Bartholic, Director of the Institute of Water Research facilitated the contract between MSU and USGS . Members of the research team included: Justin Booth, Bill Enslin, Bob Godwin, Ed Hartwick, Pam Hunt, JoAnn Render, Yi Shi, Andreanne Simard, Paula Steiner and Sharon Vennix.

USGS Michigan Water Science Center

The team leader was Dr. Howard Reeves. The team members included Steve Aichele, Beth Apple, Lori Fuller, Chris Hoard, David Holtschlag, Carol Luukkonen, Brian Neff, Cynthia Rachol, and Kirsten Wright.

Technical Support

To assist the research team, DEQ assembled a technical advisory panel of geologists, hydrogeologists, and engineers from different program areas within DEQ including, John Esch (*Superfund Section*), Kevin Kincare (*Office of Geological Survey*), Richard Mandle (*Groundwater Modeling Program*), Jeff Spencer (*Environmental Science and Services Division*) and Ron Stone (*Waste and Hazardous Materials Division*). The research team met with the technical advisory panel once a month to review progress and gather suggestions for research efforts. The project benefited greatly from the candid discussion and helpful suggestions of the technical advisory panel.

Data for the inventory and map were provided by agencies in addition to DEQ. Bob Pigg from Michigan Department of Agriculture (MDA) directed the data collection, provided the data, and reviewed the map for agricultural water use reported to MDA. Michael Kost, Ecology Program Leader from Michigan Natural Features Inventory, supplied the analysis and data for the groundwater dependent natural features listed in the Natural Features Inventory.

Additional Project Review

The Groundwater Conservation Advisory Council was briefed on two occasions – October 7, 2004 (Higgins Lake) and April 22, 2005 (Grand Rapids). A project overview and appraisal meeting was held March 1, 2005 at the Kellogg Center on the campus of MSU. Representatives from an array of stakeholder groups were invited including water supply consultants, well drilling contractors, academic hydrogeologists, local environmental health and the DEQ technical advisory group. Preliminary copies of the Glacial Aquifer and Bedrock Aquifers Yield maps were displayed at the March 15, 2005 annual meeting of the Michigan Groundwater Association. About fifty people viewed the maps and twelve made written comments concerning groundwater conditions in their various service areas. Virtually all the verbal comments were positive.

Summary of Products

The final maps and inventory items assembled to comply with P.A. 148 are summarized in this report. Detailed descriptions of the procedures used to meet each requirement are provided in the companion Technical Report for this project that is available on the project web site (gwmap.rsgis.msu.edu/). This web site is an important feature of this project. All the assembled data and analysis derived from the raw data are available on this site, in addition to the final maps required by the legislation. Although the inventory and map products provide a wealth of valuable new information processed from the compilation of existing data, decisions regarding specific groundwater uses require site-specific studies that go beyond the scope of this project.

The inventory and map products are available to end-users in three ways. Each of these provide for interactive viewing and use of the data at larger scales not possible with the small-scale maps provided in this Executive Summary. The DEQ Water Bureau web site will provide links and explanations of use for all three distribution mechanisms:

1. Web-based mapping site hosted by Remote Sensing and GIS Research and Outreach Services at MSU (gwmap.rsgis.msu.edu/). The digital data are also available for download from this site.
2. Digital data provided on compact disc for use with the Map Image Viewer software (MIV), an easy-to-use GIS software package for viewing and analyzing spatial data. The Remote Sensing and GIS Research and Outreach Services group at MSU provides this mechanism. There is a charge for this service for users other than local health departments and the DEQ.
3. The digital data will also be available for download through the State of Michigan, Center for Geographic Information (www.michigan.gov/cgi).

P.A. 148, Section 32802 (Michigan, Public Acts of 2003) specified that the "groundwater inventory and map" include the following items (a) through (h). Compliance with the requirement was met, in part, by development of the summary maps noted in the following list and included in this report.

(a) ***Location and water yielding capabilities of aquifers in the state***.

Summary maps:
1) Glacial Deposits – Estimated Yield (p. 10)
2) Glacial Deposits – Estimated Drawdown (p. 11)
3) Estimated Drawdown in Glacial Deposits Resulting from High-Capacity Well Pumpage (p. 12)
4) Bedrock Aquifers – Estimated Yield (p. 15)
5) Bedrock Aquifers – Estimated Drawdown (p. 16)

(b) ***Aquifer recharge rates in the state***.
Summary map: 6) Estimated Recharge to Glacial Deposits (p. 19)

(c) ***Static water levels of groundwater in the state***.
Summary map: 7) Estimated Depth to the Water Table (p. 20)

(d) ***Base flow of rivers and streams in the state***.
Summary map: 8) Estimated Base Flow of Rivers (p. 22)

(e) ***Conflict areas in the state (as defined by P.A. 177)***.
Summary map: 9) Groundwater Use Conflicts (p. 24)

(f) ***Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources that are identified on the natural features inventory***.
Summary map: 10) Trout Lakes and Streams, and Groundwater Dependent Resources from the Michigan NFI (p. 26)

(g) ***The location and pumping capacity of all registered industrial or processing facilities, all registered, non-agricultural irrigation facilities, and all public water supply systems that have the capacity to withdraw over 100,000 gallons of groundwater per day average in any consecutive 30-day period***.
Summary maps: 11) Non-agricultural Groundwater User by Type (p. 27)

(h) ***Aggregate agricultural water use and consumptive use, by township***.
Summary map: 12) Agricultural Water Use, by Township (p. 29)

In fulfillment of the requirement to "collect and compile groundwater data into a statewide groundwater inventory ..." the project searched the available literature for relevant theses, journal articles, abstracts, conference presentations/papers, and government documents that described groundwater characteristics anywhere in Michigan. This "statewide groundwater inventory" is available to the public through a web application described at the end of this report.

Recommendations

There is still much to learn about the groundwater resources of Michigan and their stewardship. For this issue area, Michigan's number one priority should be the maintenance and enhancement of the maps and data compiled by the GWIM Project. The team strongly recommends the following as necessary next steps to maintain, enhance, and expand upon this *initial* GWIM Project. Simply stated, this project would have been impossible without the extensive electronic database of water well records, *Wellogic*, which is maintained by DEQ. The *Wellogic* program is primarily supported by federal funding through Clean Water Act, Section 106 monies. As budgetary constraints continue to squeeze the DEQ, more Water Bureau programs are looking to this source of funding for support, threatening the long-term viability of the *Wellogic* program. Success of site-specific studies and other future efforts also will depend on a vibrant *Wellogic* program. Refinement of the groundwater yield estimates will require field mapping of glacial geology at local scales, additional characterization of the full thickness of glacial deposits, and more hydraulic characterizations of aquifers in regions that currently are data poor.

Database issues

- Continue to maintain and add documents to the groundwater Inventory.
- Continue to maintain *Wellogic* adding new well records in a timely fashion.
- Enter data from the scanned historic well records (~800,000 available) into *Wellogic*, prioritizing areas where electronic well records are scarce.
- Continue to provide outreach and technology transfer on the use and importance of *Wellogic*.
- Pursue consistency in water-use reporting requirements. Current inconsistencies include reporting either capacity or use, reporting use by facility or well, and reporting use aggregated by township.
- Develop a process to streamline the mapping of water use and provide tools to DEQ and MDA to simplify the mapping procedure as new data are submitted each year.

Mapping issues

- Explore ways to obtain hydraulic characteristics of aquifers, especially in data-poor areas, with a priority on areas of potential future water resource development.
- Update the improved bedrock topography map and the improved thickness map of the glacial deposits that were created by this project. Much of the information required for this updating task was collected and scanned during the aquifer map and inventory project.
- Develop large-scale (i.e. local) 3-D maps identifying the major confined and unconfined aquifer zones in the glacial deposits. Such a task was considerably beyond the time-line and budget of this project.
- Support and expand the detailed glacial geology mapping of the Michigan Office of Geological Survey with a focus on relating this effort to groundwater resource management.

Water balance and impact data

- Maintain the existing groundwater-level monitoring program and expand it to include both background wells that provide information on the natural variability of water levels and wells in areas of active pumping to record induced changes. The network also should include wells in the major bedrock aquifers and in a variety of glacial settings.
- Study and report on the temporal trends in the existing groundwater-level data. This analysis would provide insight to areas of Michigan that are more or less sensitive to drought, and provide a water-use and climatological context to the reported static water levels.

- Expand surface-water gaging network to improve estimates of baseflow and recharge.
- Collect low-flow streamflow measurements for currently ungaged watersheds to confirm the baseflow estimates and provide additional data to improve these estimates.
- Research practical methods to link aquifer analyses, water-use information, and baseflow and recharge estimates to evaluate the ecological impact of future groundwater resource development.

Required Elements of the Groundwater Inventory and Map

Location and water-yielding capabilities of aquifers in the State

This requirement was the most challenging owing to difficulties in determining the location and extent of glacial aquifers and in quantifying the water-yielding capability of any aquifer. The water-yielding capability (i.e. yield) from the glacial deposits that cover most of Michigan was mapped separately from the yield for the various bedrock aquifers. Although there are important heterogeneities at local scales, the general configuration of the bedrock aquifers is better known compared to aquifers within the glacial deposits.

Yield from a location in either the glacial deposits or bedrock aquifers was mapped as the estimated pumping rate that would cause a fifty-percent decrease in water level in the aquifer in that locale. This fifty-percent threshold value accounts for the generally accepted manner that high-capacity water wells operate. The yield map should **not** be viewed as a guarantee of yield from a well at a specific location.

Companion maps for the glacial deposits and the bedrock aquifers were produced to show the estimated change in groundwater level within the aquifer at a distance of 500 feet from a specified withdrawal location on the yield maps after 100 days of continuous pumping. These drawdown maps illustrate the general response to a groundwater withdrawal at the estimated yield rate in different areas of the State – they should not be used for groundwater withdrawal design purposes. A site-specific analysis of both aquifer yield and the impact of a proposed groundwater withdrawal should always be performed, especially in the case of proposed high-capacity wells.

Additional information describing and characterizing portions of the various bedrock and glacial aquifers in Michigan can be obtained from the groundwater information database that can be searched on the project web site (gwmap.rsgis.msu.edu/). Details about this search function are given in the concluding sections of this document.

Glacial Deposits

Aquifers in the glacial deposits of Michigan tend to be complex and, in many areas of the State, are extremely heterogeneous. Most glacial aquifers are identified only from very site-specific (i.e. costly) studies, and the horizontal and vertical extent and continuity of individual glacial aquifers is generally unknown. The budget and time-line of this project precluded focusing on individual aquifer units. Instead, the yield was estimated for the thickness of the glacial deposits typically used for water supply.

The major data sources used to estimate the yield from the glacial deposits included 1) *Wellogic*, an electronic database of water-well records maintained by DEQ; 2) a database of aquifer-test analyses developed and maintained by DEQ; and 3) a new glacial landsystems map compiled for this project. The glacial landsystems map provides the geologic framework that is used to regionalize the various data that were extracted from *Wellogic*. The landsystem map supported the classification of the State into areas where the anticipated amount of water that can be transmitted by an aquifer is low, intermediate, or high. The lithologies (sand, silt, clay, etc.) reported in *Wellogic* were used to develop equivalent hydraulic conductivity and transmissivity estimates that quantify the expected yield and show the heterogeneity within each landsystem.

The industry-standard minimum well yield for a small residential home is 10 – 15 gallons per minute (gpm). Several regions of minimal yield (<10 gpm) are obvious on Figure 1, notably in the areas northwest, south and southeast of Saginaw Bay, the tip of the "thumb", and southeasternmost Lower Michigan. Many areas in Delta and Menominee counties in the Upper Peninsula also exhibit poor yields. Note that in these areas, some homeowners have wells in glacial deposits that yield sufficient water. Local-scale heterogeneity (lithologic variations within 10 – 1000 meters) is very difficult to quantify and display on a statewide map. As such, site-specific investigation is always prudent when planning high-capacity groundwater withdrawals.

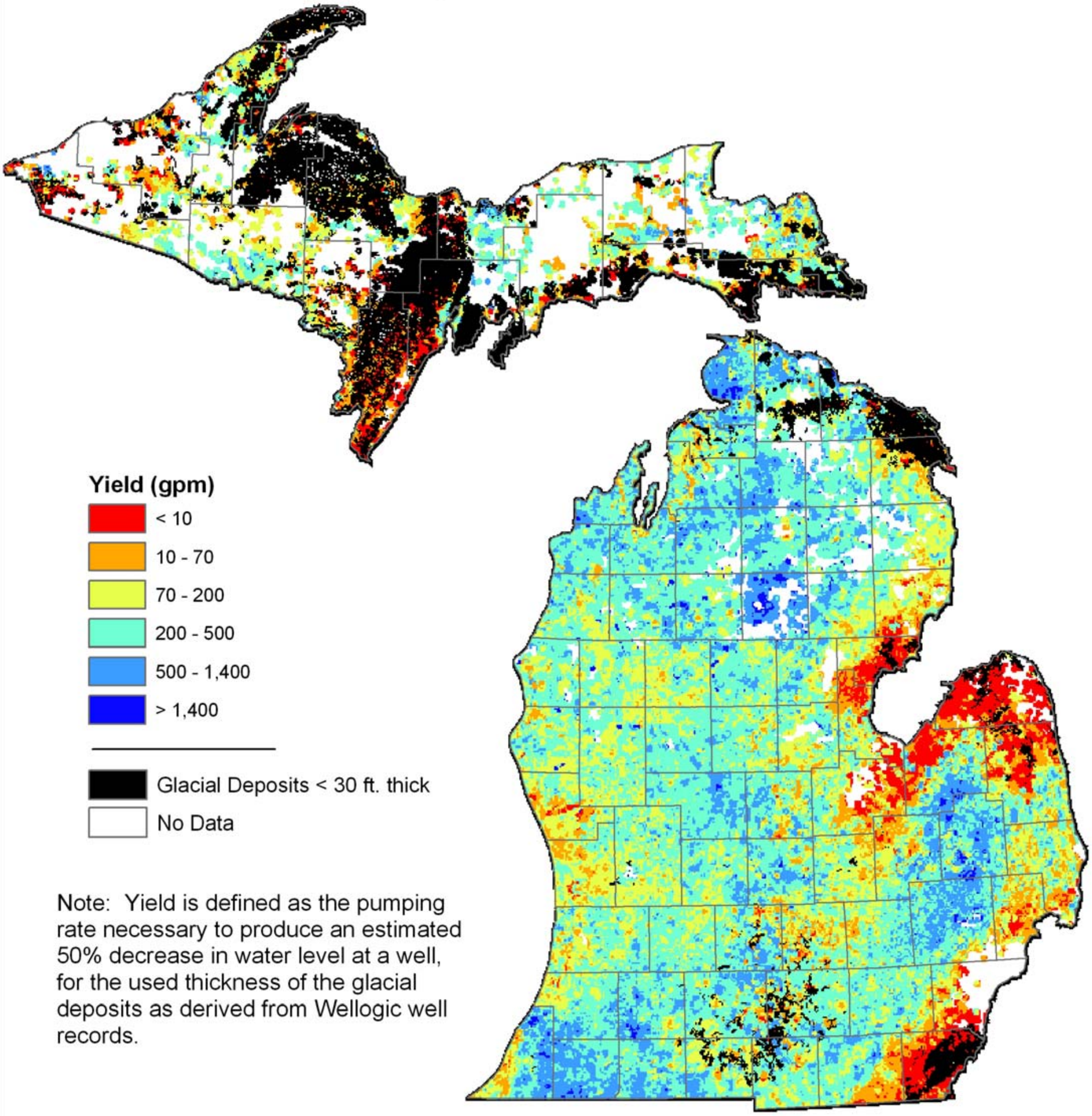
The 70 gpm yield level is the current definition of a high-capacity well. Such wells are routinely possible throughout much of Lower Michigan (excluding the areas shown in red and orange). Zones of very high yield potential are located in southwestern and south-central Lower Michigan, in the core of the "thumb" (Oakland, Lapeer and southeastern Tuscola counties), in the Houghton-Higgins lakes district of northern Lower Michigan and across the "tip of the mitt."

Areas of thin glacial deposits (<30 feet) that make legally-constructed water wells screened in the glacial deposits unlikely are shown in Figures 1 and 2. The no-data areas on these maps are defined as zones more than 2000 meters away from a well log in *Wellogic*. This 2000-meter buffer zone balances the desire to note areas that lack data in *Wellogic* with the need for a statewide estimate. If the buffer was set much smaller, the no-data areas would begin to dominate the map in the northern Lower Peninsula and across the Upper Peninsula.

The estimated drawdown map for pumping from glacial deposits (Figure 2) follows the general patterns noted for the yield map (Figure 1) with one interesting exception. Areas of low estimated drawdown (less than 5 ft) occur both where the estimated yield is moderate (70 – 200 gpm) and where it is low (< 10 gpm). In the low-yield areas, the small estimated drawdown results from the inability of the water-bearing materials to provide enough groundwater to impact a well 500 feet away. In areas of moderate yield, the available drawdown and transmissivity of the glacial deposits are such that the estimated yield can be obtained without significantly lowering the groundwater level 500 feet away. In these areas, a high-capacity well capable of pumping at a rate larger than the estimated yield might be possible (for example, by drilling a well much deeper than the typical wells in the area) and such a well could impact groundwater levels 500 feet away.

Figure 3 illustrates an example spatial analysis of the data displayed in Figures 1 and 2. Public Act 177 (Acts of 2003) established the Groundwater Dispute Resolution Program within the DEQ to investigate and resolve disputes arising from the impacts of high-capacity water wells (pumping capacity of 70 gallons per minute [gpm] or more) on small-quantity wells (pumping capacity less than 70 gpm). Figure 3 shows the estimated drawdown (data from Figure 2) resulting from groundwater withdrawals of 70 gpm or more in the glacial deposits. In many large areas of the state, the estimated drawdown exceeds 10 feet, which could adversely affect neighboring wells. It should also be noted, however, that problematic groundwater withdrawal impacts can, and do, occur in many areas of the state where the estimated yields (Figure 1) are less than 70 gpm.

Figure 1
Glacial Deposits - Estimated Yield



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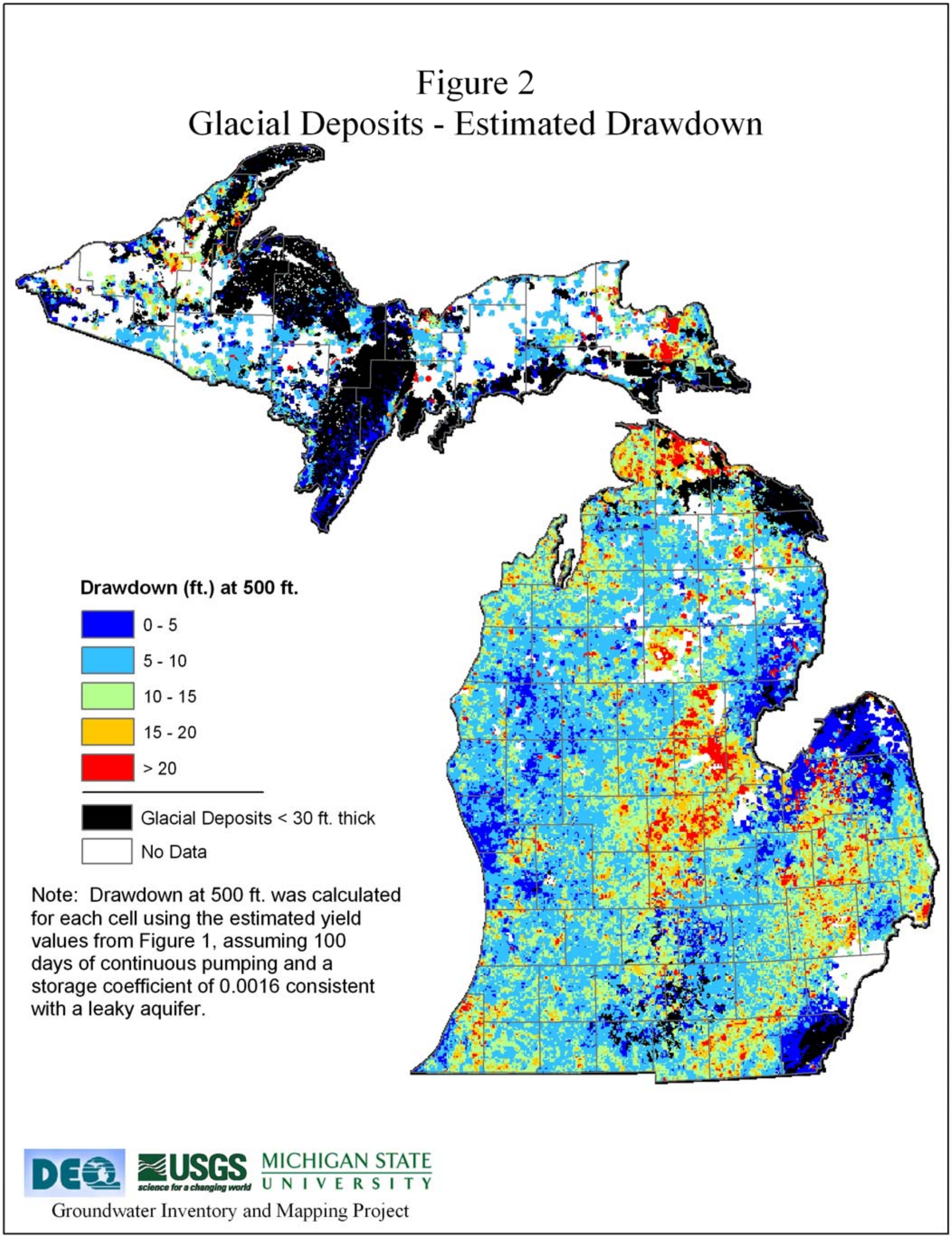
Figure 2
Glacial Deposits - Estimated Drawdown
Drawdown (ft.) at 500 ft.
0 - 5
5 - 10
10 - 15
15 - 20
> 20
Glacial Deposits < 30 ft. thick
No Data
Note: Drawdown at 500 ft. was calculated for each cell using the estimated yield values from Figure 1, assuming 100 days of continuous pumping and a storage coefficient of 0.0016 consistent with a leaky aquifer.
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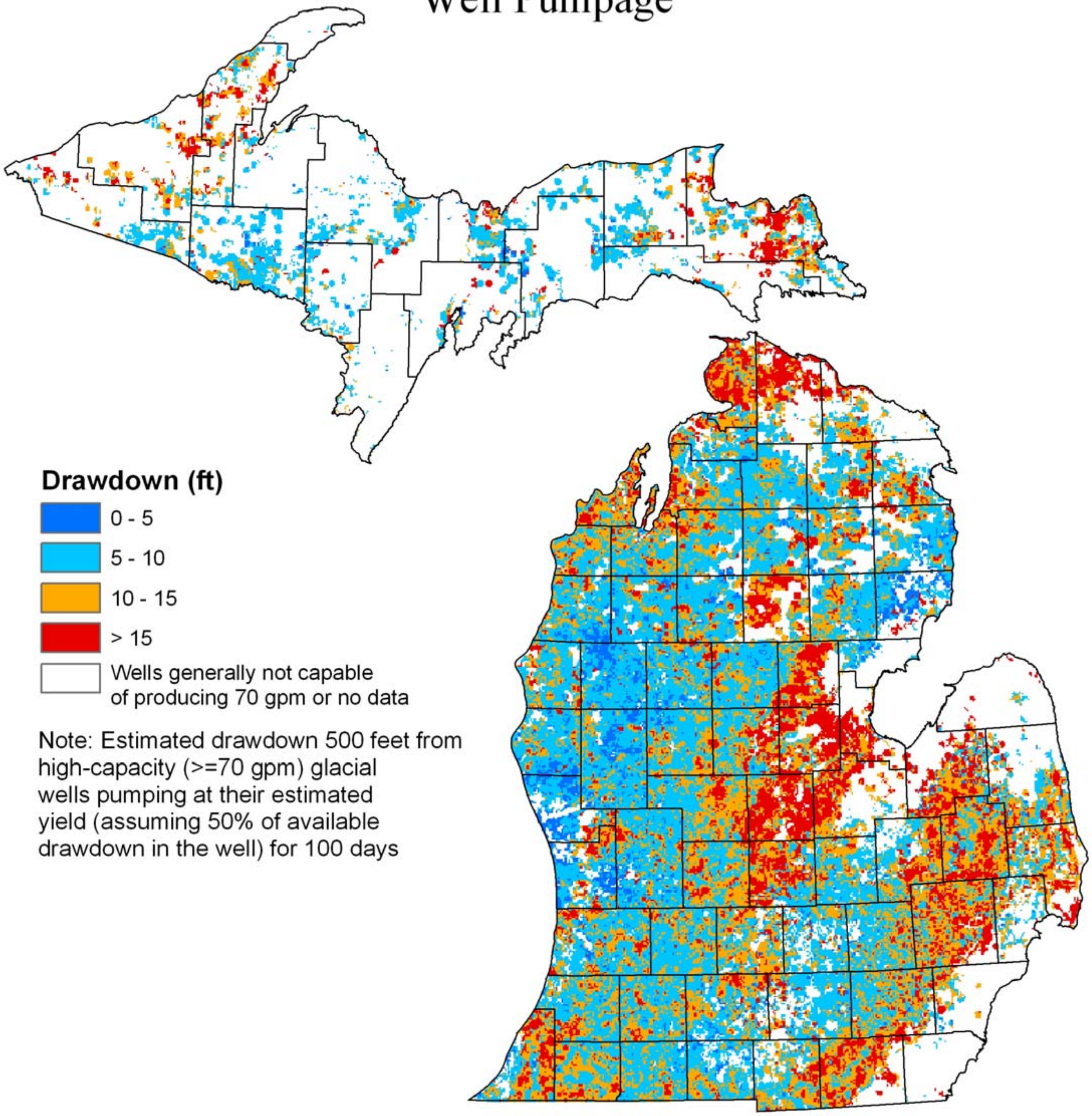
Figure 3
Estimated Drawdown in Glacial Deposits Resulting from High-Capacity Well Pumpage



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Bedrock Aquifers

Four major sources of hydrogeologic data were available to characterize the properties of the bedrock aquifers in Michigan: 1) the DEQ aquifer-test database, 2) the USGS Regional Aquifer System Analysis (RASA) aquifer-test archive, 3) hydraulic properties listed in county hydrogeologic reports, and 4) specific capacity data from some wells in *Wellogic*. The configuration of the bedrock aquifers was characterized using the state bedrock geology map (Milstein, 1987), information from the USGS Michigan Basin RASA (Westjohn and Weaver, 1998), and information from the water-well records in *Wellogic*.

The bedrock aquifer yield map (Figure 4) depicts those areas of the state where groundwater is readily available from the bedrock. The highest estimated yields from bedrock aquifers occur in the central and southern portions of the Lower Peninsula especially in Jackson, Calhoun and Barry counties where high yields are associated with a productive sandstone unit (the Marshall Formation).

Lower yields are typical from bedrock aquifers in the Upper Peninsula, the northern swath of the Lower Peninsula and in the southeast corner of the state. These aquifers are generally comprised of sandstone and carbonate units in the Upper Peninsula and predominately carbonate strata in the Lower Peninsula.

In the Lower Peninsula, the white areas on Figure 4 are generally characterized by shale bedrock units that normally do not serve as aquifers, such as the Coldwater Shale that underlies much of southwestern and southeastern Lower Michigan and an arcuate swath from Mason to Alcona counties in the northern Lower Peninsula. Much of the western Upper Peninsula is dominated by hard-rock units that only produce groundwater along localized fracture traces. Nevertheless, there are residential wells in these areas of the State that derive water from fractures in the upper part of these “non-aquifer” units.

The estimated drawdown map for groundwater withdrawals from bedrock aquifers at the estimated yield rate is depicted in Figure 5. Comparing Figures 4 and 5, at least four groundwater withdrawal regimes across Michigan are apparent:

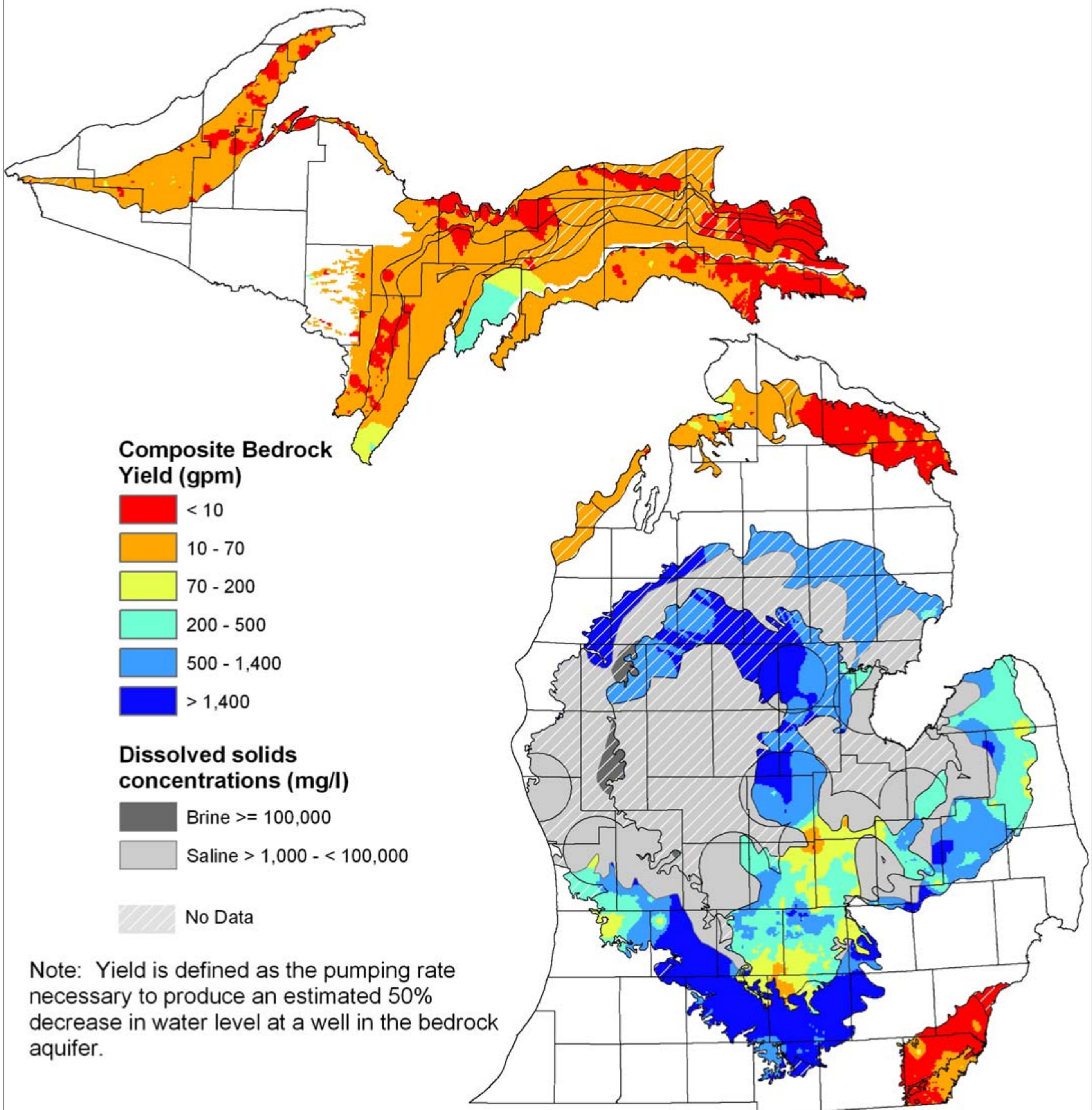
1. <u>Low-yield areas exhibiting small drawdown values</u>. In these areas, the estimated yields are so small that the groundwater withdrawal does not cause significant drawdown 500 feet away. This condition exists across a large portion of the Upper Peninsula, as well as in the northern swath and southeast corner of the Lower Peninsula.
2. <u>High-yield areas with large drawdown values</u>. In these locales, the aquifer characteristics allow for large yields at the expense of a great deal of drawdown. Such conditions occur in the central and north-central portions of Lower Michigan and in four restricted areas in Barry, northeastern Jackson, northern Ingham and northwestern Lapeer counties (associated with portions of the Saginaw Formation and the Marshall Sandstone).
3. <u>High-yield areas exhibiting small drawdown values</u>. In these places, the aquifer properties promote minimal drawdown values even at high rates of withdrawal. These conditions are common in a narrow band across northeastern Calhoun, southern Jackson and northern Hillsdale counties (all associated with the southernmost margin of the Marshall Sandstone).

4. Moderate-yield areas with moderate drawdown values. The hydraulic properties of some bedrock aquifers are such that both the estimated yields and the associated drawdown amounts are moderate. The Saginaw formation beneath portions of Shiawassee, Clinton, Eaton and Ingham counties exhibits these characteristics as does the Marshall Sandstone in parts of Sanilac and Huron counties.

Another noteworthy attribute of the bedrock aquifers in central Lower Michigan is shown by the gray and dark gray overprint on Figures 4 and 5. These are zones within the rock units where the dissolved solids concentrations in the groundwater exceed 1,000 milligrams per liter (more than twice the recommended drinking water limit). For lack of practical alternative water supplies, some residential well owners utilize this low-quality groundwater. This is especially common in the area around Saginaw Bay.

The map reader should take careful note of the white diagonal stripe pattern across large areas of central Lower Michigan and more restricted areas in the eastern Upper Peninsula on Figures 4 and 5. These parts of the state lacked sufficient data to accurately predict both the yield and the drawdown levels. The various colors beneath the stripe pattern (depicting yield or drawdown) are shown to indicate the areal extent of the various bedrock aquifers. The yield and drawdown values in these areas are notably unreliable.

Figure 4
Bedrock Aquifers - Estimated Yield



Note: Yield is defined as the pumping rate necessary to produce an estimated 50% decrease in water level at a well in the bedrock aquifer.

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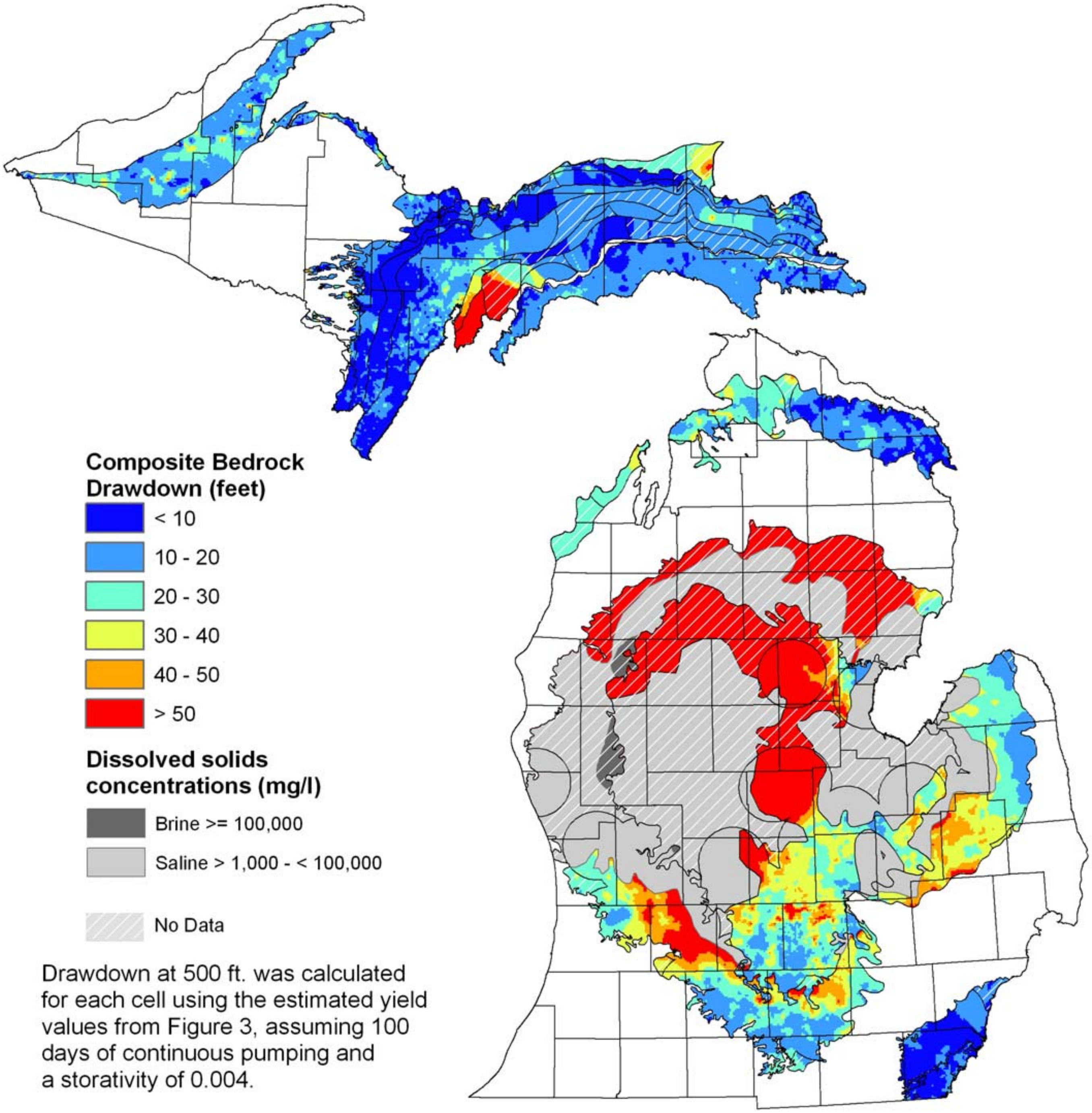
Figure 5
Bedrock Aquifers - Estimated Drawdown



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Recharge

Recharge typically refers to the amount of precipitation, either rainfall or snowmelt, that infiltrates through the ground and reaches the water table aquifer. Deeper aquifers generally are recharged with water from shallower systems. Groundwater discharge is water that leaves an aquifer through boundaries including rivers, wetlands, and lakes. The approach used to estimate recharge is based on statistical regression of groundwater discharge (baseflow) estimates derived from stream-gaging records. The assumption is made that recharge to the shallow aquifer system is equal to baseflow. The regression technique expands on the work for the lower peninsula of Michigan by Holtschlag (1996). This method is appropriate for the shallow aquifer system (typically in the glacial deposits) that delivers most baseflow to streams and provides a long-term (1 – 80 year) average estimate of recharge for moderate areas (up to 500 square miles) (Scanlon and others, 2002). Note that most bedrock aquifers in Michigan do not possess a strong hydraulic connection to the gaged streams and that the recharge map does not apply to the water delivered to bedrock aquifers from the overlying glacial deposits or through adjacent bedrock units.

The baseflow estimates discussed below were used to estimate recharge as detailed in the Technical Report. Note that although the spatial distribution of streamflow gages in the Lower Peninsula (totaling 162) was generally adequate to represent most landscape settings, only 46 gages were available in the Upper Peninsula. There were too few Upper Peninsula gages to provide an adequate number of observations to support the incorporation of land cover and surficial geology data into the models. This is why the recharge map (Figure 6) in the Upper Peninsula is notably less detailed than in the Lower Peninsula. This also means that the influences of surficial geology, such as the reduction in recharge and baseflow associated with the low-permeability lacustrine deposits in the eastern Upper Peninsula, as well as the effects of land cover, have been ignored in the estimation procedure undoubtedly leading to an overestimation of recharge in this part of Michigan.

A common misconception is that groundwater development can be designed such that pumping does not exceed recharge. Such a view fails to recognize that a withdrawal designed to pump all available recharge leaves no groundwater to provide baseflow to streams, support ecology, or prevent intrusion of poor-quality groundwater from adjacent geologic units. It also does not consider well-to-well interference such as that addressed by P.A. 177. The source of groundwater to wells must be recognized and the impact of pumping a well on the groundwater system must be understood in order to place the recharge estimate map in its proper context (Alley and others, 1999).

Before pumping, the groundwater system is in a state of dynamic equilibrium. Recharge into the system is balanced by discharge out of the system (this is the basis of the assumption used in equating estimated baseflow with long-term recharge). When recharge exceeds discharge, the groundwater level in an aquifer will rise and more water is held in storage in the system. When discharge exceeds recharge, groundwater levels decline and water is removed from storage. These changes in groundwater levels occur on seasonal, annual and long-term cycles. When a well is pumped, water will come from one or more of these three sources: (1) a change in storage in the system by lowering the water level, (2) an increase in recharge to the aquifer, or (3) a decrease in discharge to surface water from the aquifer.

When a groundwater withdrawal occurs, water is first removed from storage and the water level in the aquifer adjacent to the well is lowered. The change in water level extends outward from the well some distance depending on the hydraulic characteristics of the aquifer. For most aquifer systems, a new equilibrium state is reached by associated decreases in discharge from the aquifer system, although in some cases recharge to the aquifer system may be increased (e.g. induced recharge from surface water). The balance between removal from storage, increase in recharge, decrease in discharge and the time required for these changes to occur after a well is pumped are all determined by the hydraulic characteristics of the aquifer system. The recharge rate plays a role in the behavior of the aquifer in response to pumping, but it cannot be used as the sole indicator of the water resources potential for an area.

Static Water Levels

Mapping static water levels for all aquifers of the State, as called for in P.A. 148, is problematic for two major reasons. First, although the static water level is recorded on many of the water well records in *Wellogic*, the wells must first be grouped together by aquifer so that the various groundwater levels are not inappropriately mixed. Only rarely, and then only in small areas, are glacial-aquifer maps available due to the heterogeneity of the glacial deposits across much of Michigan. As a result, grouping wells that are screened in the glacial deposits by aquifer is very difficult. Second, the reported static water levels, even for wells in the same aquifer system, may vary considerably across the several decades of reporting in *Wellogic* due to seasonal variability, climatic changes, changes in use, and inaccuracy of reported levels.

A greatly-improved, statewide water table map was compiled to partially fulfill this mandate (Figure 7). This mapping effort built upon a prototype version of a similar map that had been compiled by RS&GIS, MSU as part of the very successful Source Water Assessment Program (Michigan Department of Environmental Quality, 2004). The water table is the upper surface of the saturated zone of the earth. The water table map was compiled from several existing, digital, geospatial data sets, including surface hydrography, topography, soils, wetlands and selected well records from *Wellogic*. The improvements over the previous version came primarily from the incorporation of newly available soils data, new analyses of the lithology data in *Wellogic* that identified wells screened in unconfined glacial aquifers and improved computerized interpolation methods. The “data problem” areas, shown in red on Figure 7, result from interpolation artifacts in data-poor areas that coincided with high-relief terrain.

To supplement the water table map, approximately 200 plots of groundwater levels based on observations collected at USGS observation wells across Michigan are provided in order to document both natural and pumping-induced variations in groundwater levels in both glacial deposits and bedrock aquifers. These plots are available on the project web site (gwmap.rsgis.msu.edu/) and to help illustrate the temporal trends in groundwater levels and show water levels in a number of bedrock aquifers not addressed in Figure 7.

Figure 6
Estimated Recharge to Glacial Deposits

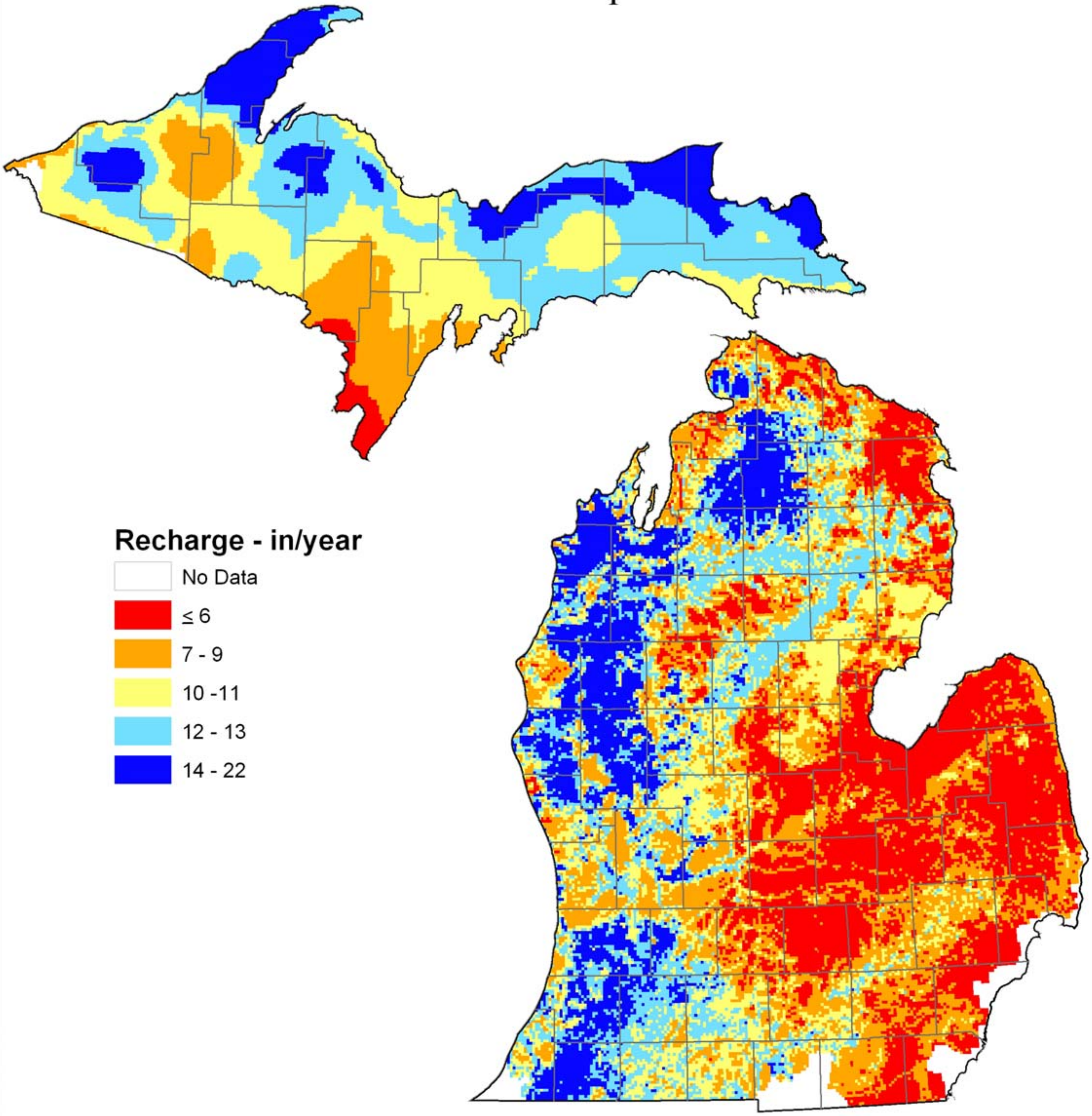

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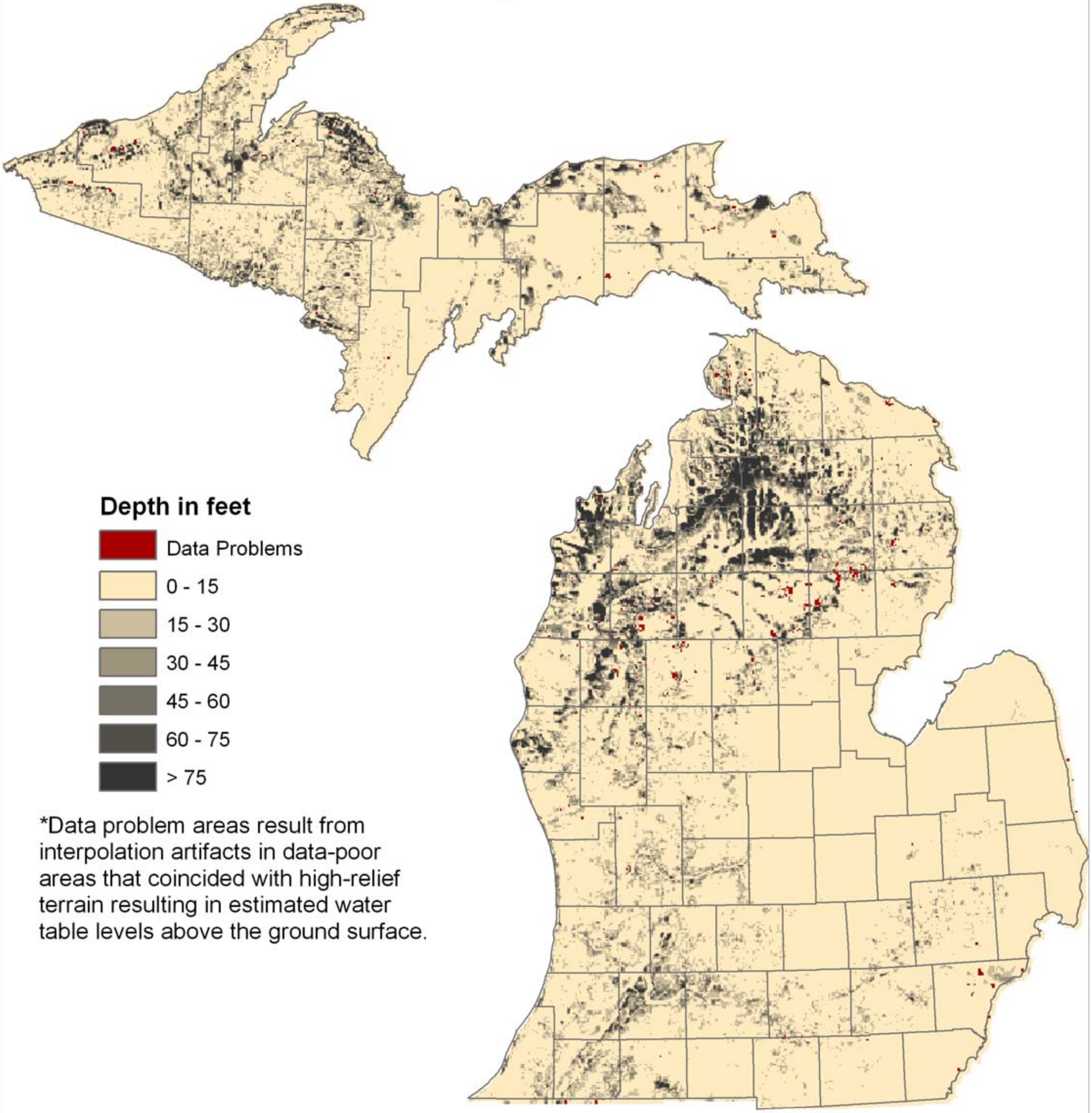
Figure 7
Estimated Depth to Water Table



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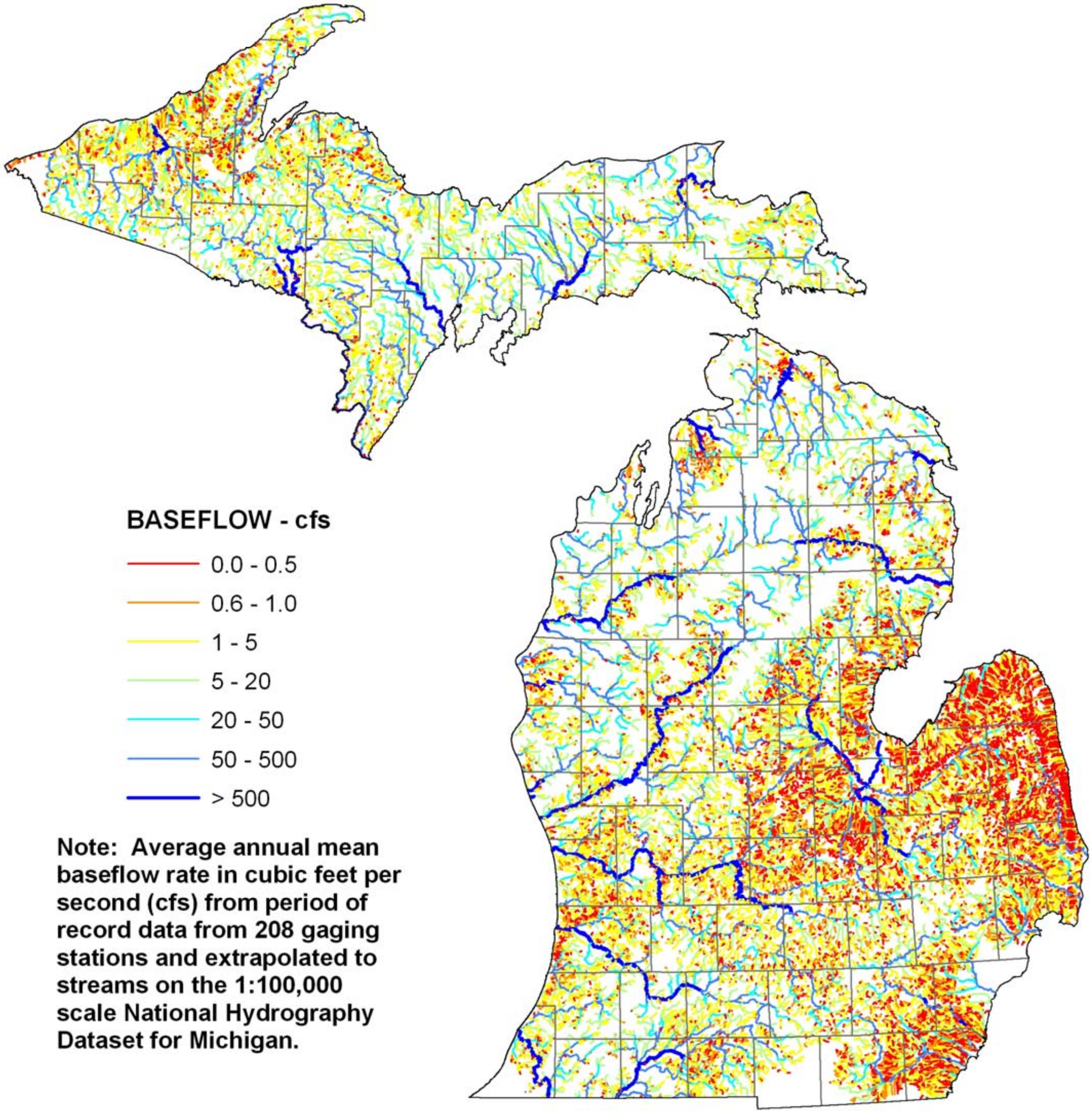
Baseflow of Rivers

The baseflow of a stream or river is the amount of groundwater discharged from an aquifer to the watercourse. This discharge occurs year-round, and fluctuates seasonally depending on the level of the water in the aquifer. Over the course of a year, assuming no change in the quantity of water stored in the aquifer, the total baseflow is assumed to equal the total groundwater recharge for a watershed. Baseflow is supplemented by direct runoff during and immediately after precipitation or melt events, resulting in peaks on a hydrograph showing stream flow through time. The process of dividing these peaks into base flow and runoff is called hydrograph separation.

Hydrograph separations were completed for all USGS stream flow-gaging stations in Michigan that had more than 10 years of daily records. Sites that were clearly affected by upstream impoundments (lakes, dams) were excluded. No attempt was made to detect or correct for trends in the data. This may lead to some errors in the comparison of streams with data from different time periods if there is an underlying temporal trend in the data, but inclusion of all records in the analysis was necessary to increase the data pool and provide better spatial coverage.

Watersheds were delineated for each of the 208 stream flow-gaging stations, and various characteristics of each watershed, such as topographic relief, surficial geology, land cover, growing degree days, annual and winter-season precipitation, and others were tabulated. Regression modeling, described in the Technical Report, was used to estimate the baseflow for each steam segment of the 1:100,000-scale National Hydrography Dataset as shown in Figure 8.

Figure 8
Estimated Baseflow of Rivers



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Conflict Areas Per P.A. 177

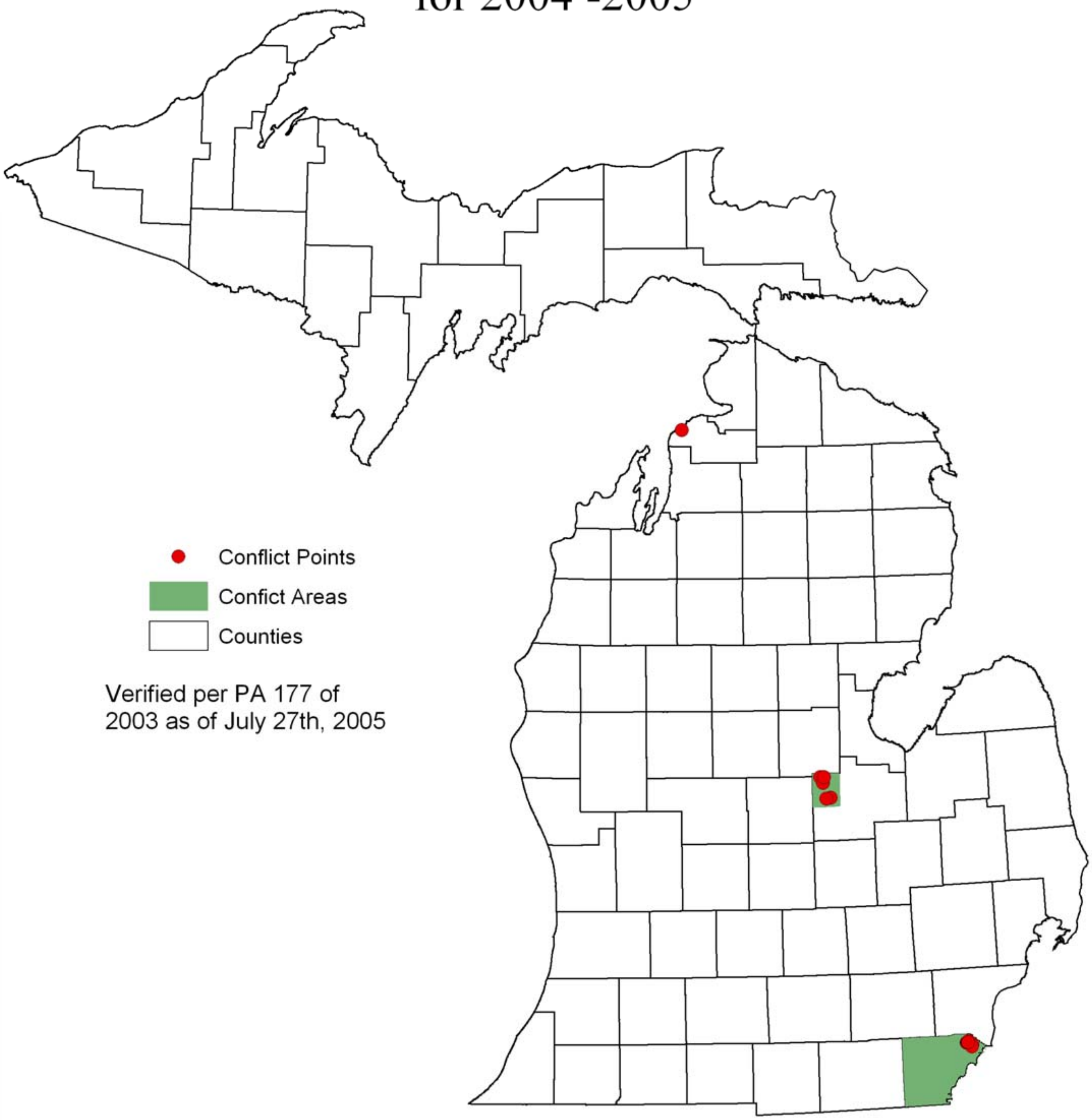
A groundwater-conflict resolution procedure was established by P.A. 177 (Michigan, Public Acts of 2003). The Groundwater Dispute Resolution Program within the DEQ investigates and resolves disputes arising from the off-site impacts of high-capacity water wells. If a small quantity well (defined as a well capacity less than 70 gallons per minute [gpm]) fails to produce its normal supply of water or fails to produce potable water and the owner has credible reason to believe the problem was caused by a high-capacity well (70 gpm or more), a complaint can be filed with the DEQ, Water Bureau. An assessment of the affected water well by a licensed water well drilling contractor maybe required to rule out mechanical problems as the cause of the well failure.

The DEQ will investigate the complaint to determine if the problem is caused by the lowering of groundwater by a high-capacity well and then make a diligent effort to resolve the dispute. If the suspected high-capacity well is an agricultural well, the complaint is referred to the Michigan Department of Agriculture, Environmental Stewardship Division, for investigation. Resolution of a groundwater dispute typically involves restoration or replacement of the small-quantity water well or connection to a municipal water system, with the high-capacity well owner reimbursing the complainant and the DEQ for costs incurred.

As of July 27, 2005, a total of 43 complaints had been received by the DEQ Groundwater Dispute Resolution Program. Of these, 17 were determined to be invalid, another 17 have been resolved and nine complaints remain unresolved. Of the 17 valid and resolved complaints, 11 involved high-capacity wells used for quarry dewatering (located in Charlevoix and Monroe counties) and six involved high-capacity agricultural wells (all in Saginaw County).

Figure 9 shows the location of the 17 valid and resolved complaints, and the two declared conflict areas. As required by the statute, the Director of the DEQ declared four townships in Saginaw County and all of Monroe County as areas where there is the greatest risk for potential groundwater disputes.

Figure 9
PA 177 Groundwater Use Conflicts for 2004 -2005



Groundwater Inventory and Mapping Project

Trout Lakes and Streams and Groundwater-dependent Resources on the Natural Features Inventory

On October 12, 2000, the Director of the Department of Natural Resources ordered that certain lakes and streams or portions of streams be designated as trout lakes or trout streams. These designated trout lakes and streams are shown on Figure 10.

The Michigan Natural Features Inventory (MNFI) is a cooperative program of Michigan State University Extension and the Michigan Department of Natural Resources to identify, evaluate and map the locations of the rarest species and exceptional examples of natural communities in Michigan. MNFI manages the continuously-updated Biological and Conservation Database. This database lists and describes 74 natural communities currently recognized by MNFI, of which 28 are considered "groundwater dependent." These also are shown in Figure 10. It should be noted, however, that there are numerous other groundwater dependent natural resources throughout Michigan that are not shown on this map because they have not yet been surveyed by the MNFI. Most persistent lakes, streams and wetlands are groundwater dependent.

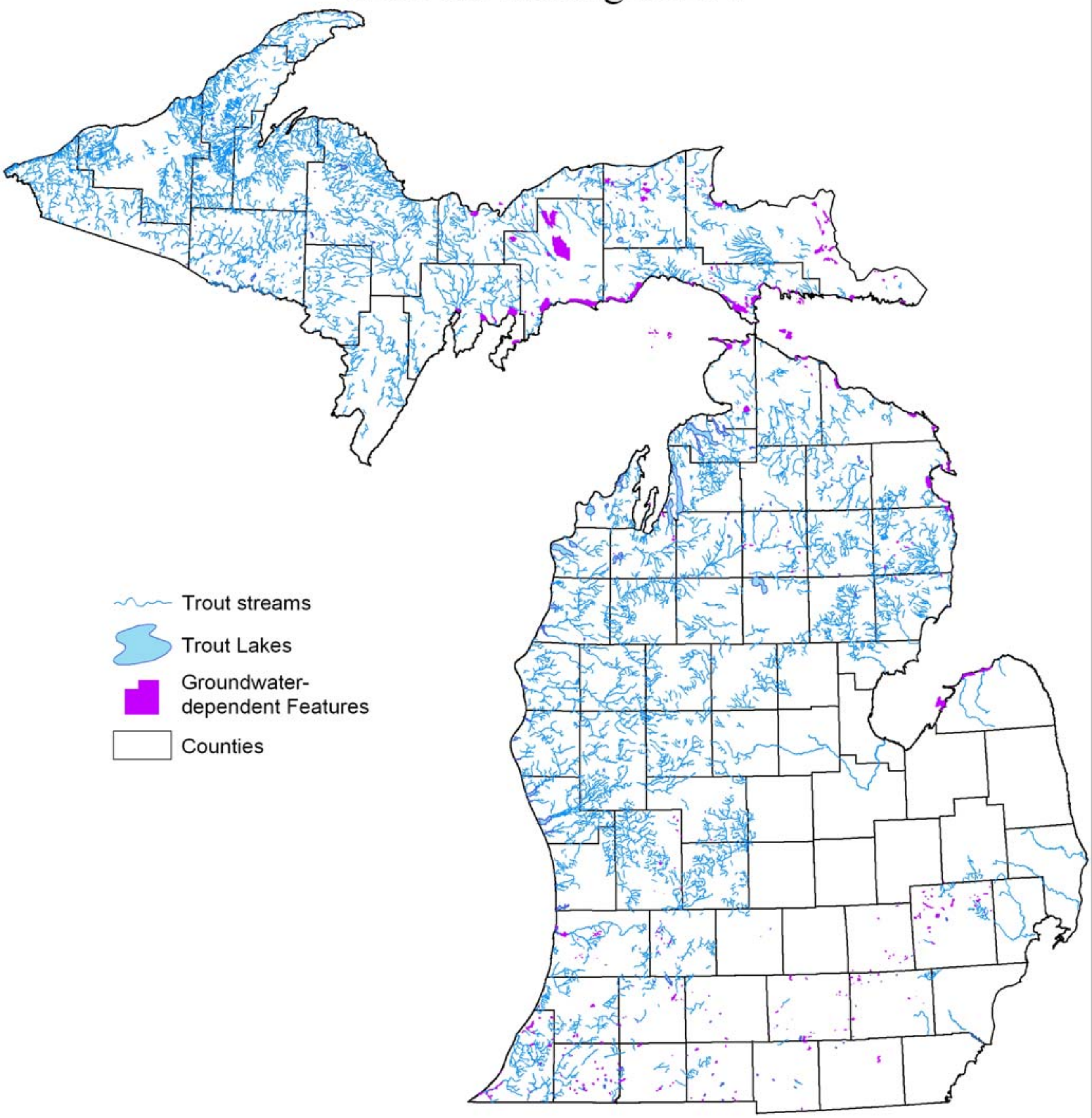
Water Use Reported to Michigan Department of Environmental Quality

Thermoelectric power generation, industrial/manufacturing, public water supply, and non-agricultural irrigation facilities throughout Michigan report water use information to the DEQ. The data shown on Figure 11 represent groundwater withdrawals made during the 2003 calendar year, based on measurements or estimates made by facility personnel.

Water withdrawal data reported under Public Act 399 of 1976, as amended, include information reported through the water supply program at DEQ by all community public water systems that withdraw groundwater. Thermoelectric power generation, industrial/manufacturing, and non-agricultural irrigation facilities with a pumping capacity of more than 70 gallons per minute (100,000 gallons per day averaged over any 30-day period) are required to report to the DEQ under Part 327, P.A. 451 of 1994, as amended. All withdrawals in this data set are defined as groundwater for the purpose of this project. However, some withdrawals reported by non-agricultural irrigators come from combined well and pond sources and include a combination of groundwater and surface water.

The accuracy of the reported data varies from measured to estimated, with metering more frequent for community water supplies and thermoelectric power plants than for industrial/manufacturing facilities and non-agricultural irrigators. In some instances where groundwater withdrawal data were not reported for 2003, facility data from a previous year were used. Since non-agricultural irrigation water withdrawals typically occur only during the May to September period, comparisons with other facility types require careful scrutiny as the posted values are all annualized averages.

Figure 10
Trout Lakes and Streams and
Groundwater-dependent Resources
from the Michigan NFI



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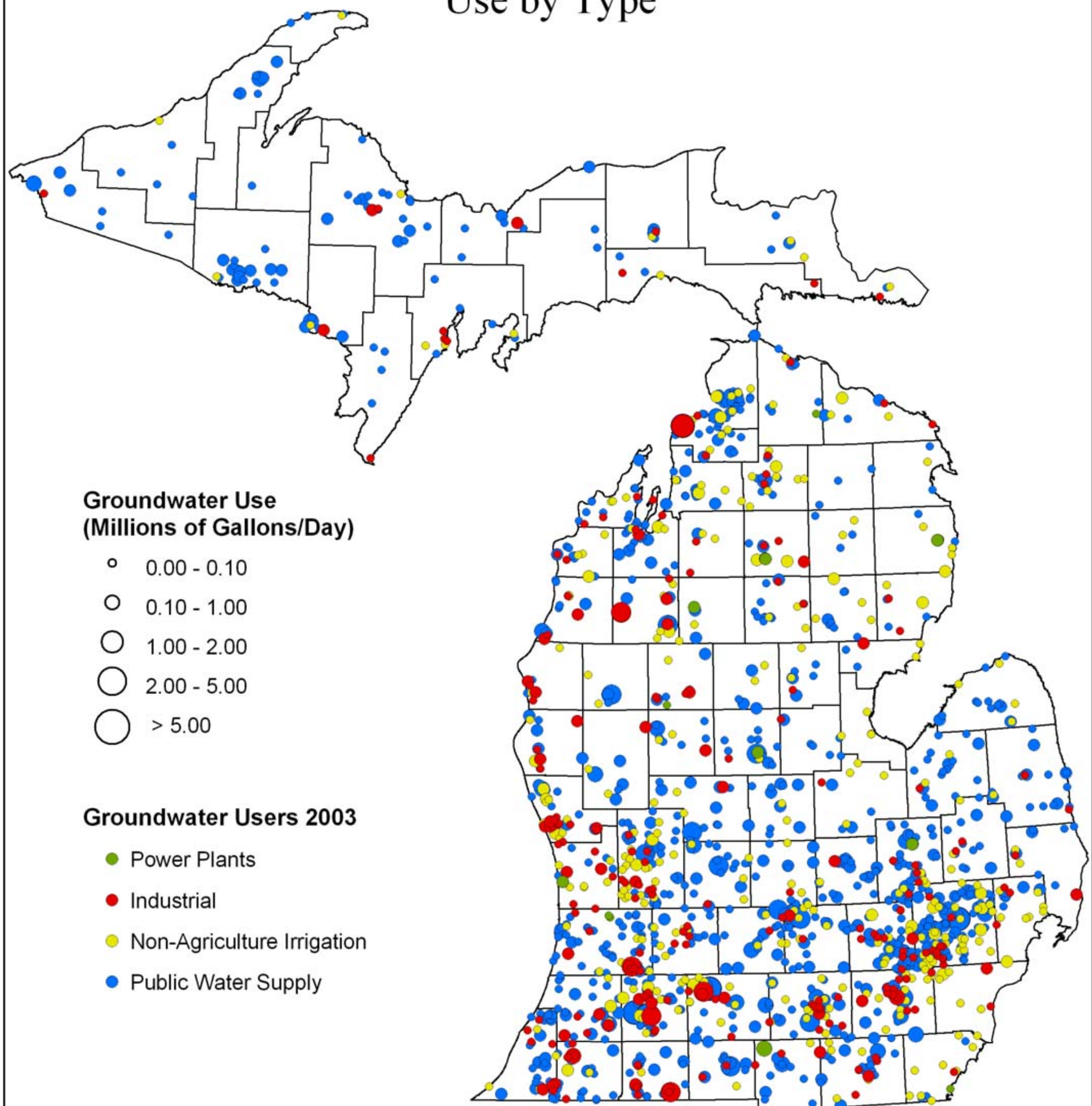
Groundwater Inventory and Mapping Project

Figure 11
Non-Agricultural Groundwater Use by Type



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Groundwater Inventory and Mapping Project

Agricultural Water Use Reported to Michigan Department of Agriculture

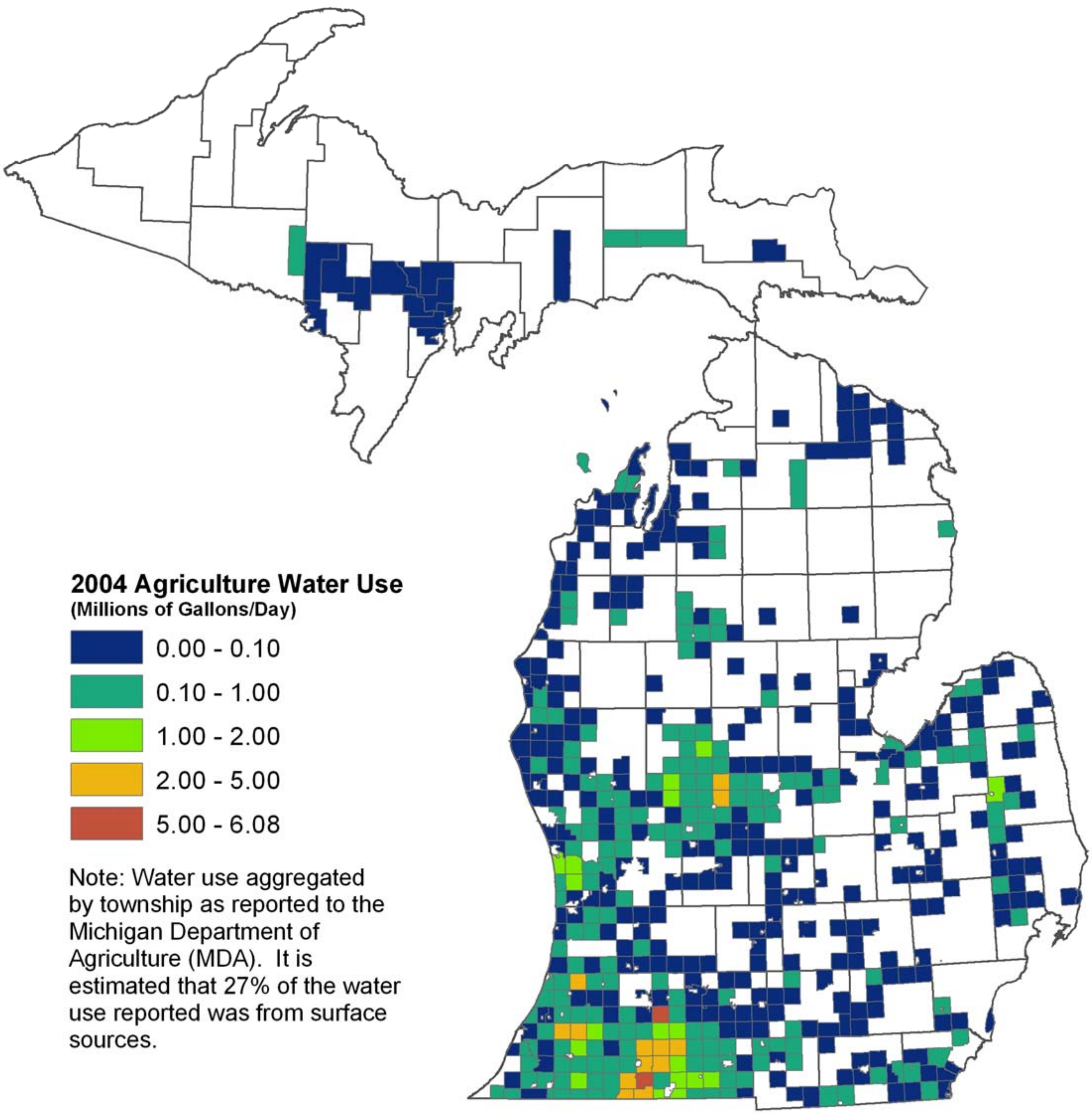
Water use was reported to the MDA by agricultural producers in the state that met water pumping capacity thresholds (70 gpm) during the 2004 calendar year. At least 90 percent of the water use reported was for irrigation. This agricultural water use, aggregated by political township as required by P.A. 148, is shown in Figure 12. It is estimated that 27% of the reported water use was withdrawn from surface water sources. Michigan and the other Great Lakes states have agreed that 90 percent of agricultural irrigation water use is consumptive. The proportion of other agricultural water uses that is consumptive varies by use.

Water use reporting forms were mailed to all agricultural producers who registered with the MDA. Forms were also made available on the MDA web site. Data mailed back to MDA were entered into a database and water use was attributed to political townships. Water use was reported in a variety of units (gallons, acre-feet, and acre-inches), but these were converted to millions of gallons per day (MGD) for consistency with other water use reporting. Obvious errors made by reporting producers were corrected; otherwise, all data were entered as reported. Water use was then aggregated by political township.

In addition to the water use in this section being reported by township, agricultural water withdrawals typically occur only during May through September. To be consistent with the previous section (non-agricultural groundwater use), the mapped values are annualized averages. As mentioned above, the reported agricultural water use data include both groundwater and surface water withdrawals. As a result, comparisons with the facilities shown on Figure 11 require careful scrutiny.

An MDA comparison of the 2004 reported agricultural water withdrawals with the 2002 NASS irrigation survey reveals that MDA received reports covering 69.7% of the irrigated acres tabulated by NASS. By comparison, the non-agricultural groundwater use reported above has an estimated reporting rate exceeding 90%. This is the first year of agricultural water use reporting and, hopefully, the percentage of irrigators reporting will improve as the program continues.

Figure 12
Reported Agricultural Water Use



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Groundwater Inventory and Mapping Project

Groundwater Data Inventory and Bibliography

In fulfillment of the mandate by Section 32802 (1) of P.A. 148 to "collect and compile groundwater data into a statewide groundwater inventory ..." the project searched the available literature for relevant theses, journal articles, abstracts, conference presentations/papers, and government documents describing groundwater characteristics in Michigan. Over 220 documents and applicable map plates were digitally scanned and are available on the project web site (gwmap.rsgis.msu.edu/). The full bibliography containing 464 citations is also available on this web site.

Many of the scanned documents were categorized into the Groundwater Information Database that supports web-based queries to find 1) written summaries of the hydrogeologic characteristics for each county, 2) the type of wells, range of transmissivity and storativity, and amount of water used for each county, 3) reports pertaining to the groundwater resources in Michigan by location, author, watershed name or hydrologic unit code, or 4) aquifer data for wells listed in reports sorted by county, type of aquifer, and/or type of test. A brochure at the back of this Executive Summary highlights the components of this Groundwater Information Database.

Distributing the Groundwater Maps to the Public

All of the maps and supporting data from the GWIM Project have been made available to public through three mechanisms. Each of these provide for interactive viewing and use of the data at various scales not possible through the summary maps provided in this Executive Summary. The DEQ Water Bureau website will provide links and explanation of use for all the distribution mechanisms:

1. Web-based mapping site hosted by Remote Sensing and GIS Research and Outreach Services at MSU (gwmap.rsgis.msu.edu/). A brochure at the back of this Executive Summary highlights the main components of this mapping application.
2. Digital data provided on compact disc for use with the Map Image Viewer (MIV), a GIS software package for viewing and analyzing spatial data. The Remote Sensing and GIS Research and Outreach Services group at MSU provides this mechanism. There is a charge for this service for users other than local health departments and the DEQ.
3. The digital maps can also be downloaded from the State of Michigan, Center for Geographic Information web site (www.michigan.gov/cgi).

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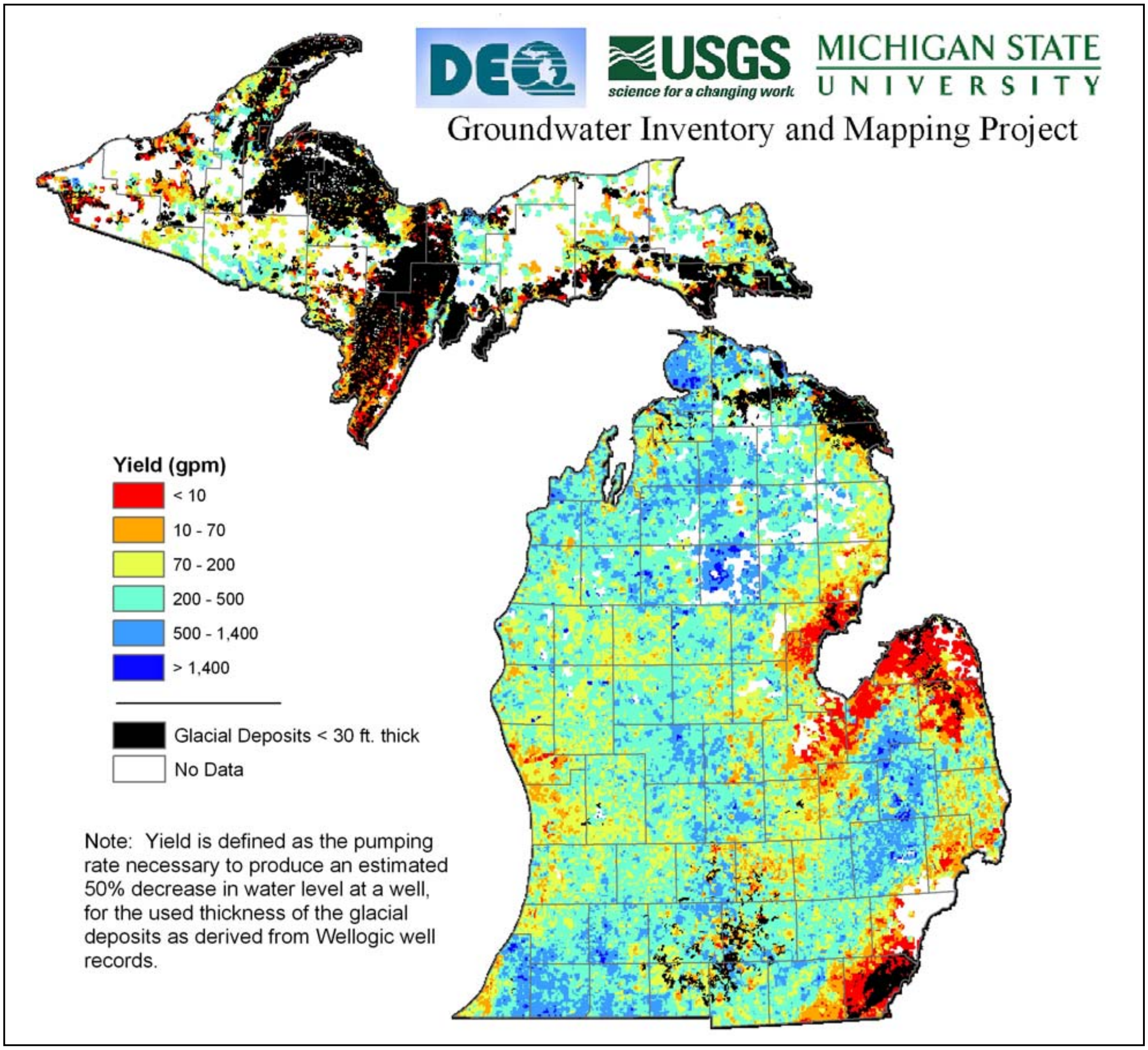
State of Michigan
Public Act 148
Groundwater Inventory and Map (GWIM) Project

Technical Report



March 2006

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Chapter 1 Introduction

1.1 Overview

Public Act 148, Section 32802 (Michigan, 2003a) requires the Department of Environmental Quality (MDEQ) to create a groundwater inventory and map that includes eight specific requirements, a general requirement for a groundwater inventory, and a directive to make the map and inventory accessible by the public. This document details the map and inventory created by MDEQ in a cooperative research project with the U.S. Geological Survey (USGS) and Michigan State University (MSU). The act went into effect on August 8, 2003 and required that this work be completed by August 8, 2005. In a separate but related effort, Public Act 148, Section 32803 (Michigan, 2003a) created a Groundwater Conservation Advisory Council. The Council report is due to the legislature in February, 2006. The Council was informed of the progress of the inventory and map, and the final inventory and map has been made available to the Council to assist with generation of their report.

1.2 Financial Support

This project was funded through a joint funding agreement between the DEQ and USGS in the amount of $900,000. The MSU team members were funded through the USGS State Water Resources Research Institute Program to the Institute of Water Research ($453,000 from the DEQ-USGS joint funding agreement). The USGS Cooperative Water Program provided additional funding for this study in the amount of $250,000. The total project budget, not including the in-kind staffing contributions from the DEQ, was $1,150,000.

In-kind staff contributions by the DEQ included oversight of the project by an engineer and geologist in the Water Bureau (WB). Extensive contributions to the project were made by WB management and other support staff. The DEQ technical advisory committee included representation from Environmental Sciences and Services, Office of Geological Survey, Remediation and Redevelopment, and Waste and Hazardous Materials divisions. The technical advisory committee met on a monthly basis. Overall, it is estimated that DEQ annual staff costs to administer this project was 2 FTEs. The extensive participation and oversight by DEQ staff resulted in many improvements and contributed to many enhancements of the products produced by the GWIM Project.

1.3 Project Team

The project team consisted of personnel from DEQ, MSU, and USGS.

1.3.1 Michigan Department of Environmental Quality

The team leaders were Brant Fisher and Joseph Lovato, directed by Wm. Elgar Brown. Project support was provided by Andrew LeBaron, Ronda Page and Dan Diebolt, Source Water Protection Unit, Drinking Water and Environmental Health Section, Water Bureau. Ron Van Til, Water Use Program, provided required data for the mapping effort, as did Kristen Philip, Community Drinking Water Unit, who compiles these data for public water supplies. Chuck Thomas, Upper Peninsula District Office, provided a great deal of help on the aquifer distribution and use for the Upper Peninsula. Mike Gaber and Dave DeYoung, Well Construction Unit, provided insight on the relationship between the mapping project and the Groundwater Dispute Resolution Program, which was established by Public Act 177 (Acts of 2003).

1.3.2 Michigan State University

The team leaders were Dr. David Lusch (Remote Sensing & GIS Research and Outreach Services – Department of Geography, and Institute of Water Research) and Steve Miller (Department of Biosystems and Agricultural Engineering, and Institute of Water Research). Dr. Jon Bartholic, Director of the Institute of Water Research facilitated the contract between MSU and USGS . Members of the research team included: Justin Booth, Bill Enslin, Bob Godwin, Ed Hartwick, Pam Hunt, JoAnn Render, Yi Shi, Andreanne Simard, Paula Steiner and Sharon Vennix.

1.3.3 USGS Michigan Water Science Center

The team leader was Dr. Howard Reeves. The team members included Steve Aichele, Beth Apple, Lori Fuller, Chris Hoard, David Holtschlag, Carol Luukkonen, Brian Neff, Cynthia Rachol, and Kirsten Wright.

1.4 Technical Support

To assist the research team, DEQ assembled a technical advisory panel of geologists, hydrogeologists, and engineers from different program areas within DEQ including, John Esch (*Superfund Section*), Kevin Kincare (*Office of Geological Survey*), Richard Mandle (*Groundwater Modeling Program*), Jeff Spencer (*Environmental Science and Services Division*) and Ron Stone (*Waste and Hazardous Materials Division*). The research team met with the technical advisory panel once a month to review progress and gather suggestions for research efforts. The project benefited greatly from the candid discussion and helpful suggestions of the technical advisory panel.

Data for the inventory and map were provided by agencies in addition to DEQ. Bob Pigg from Michigan Department of Agriculture (MDA) directed the data collection, provided the data, and reviewed the map for agricultural water use reported to MDA.

Michael Kost, Ecology Program Leader from Michigan Natural Features Inventory, supplied the analysis and data for the groundwater dependent natural features listed in the Natural Features Inventory.

1.5 Additional project review

On March 1, 2005, the project sponsored an appraisal meeting with key stakeholder groups to provide them with an overview of the project and the proposed methods, show them the initial results of the glacial aquifer characterization effort, and receive any comments or concerns that they may have regarding the project.

Fifty individuals representing the water well drilling community, academic hydrogeologists, local health departments and groundwater consultants were invited to attend. Unfortunately, a major snow storm occurred during the night of February 28th and into the morning of March 1st. As a result, only 18 participants were able to attend. The invitee and attendee list is presented in Appendix 8.10.

Dr. Lusch presented a brief overview of the project at the 77th Annual Michigan Groundwater Association Convention in Lansing, Michigan on March 16, 2005. More importantly, the Association generously provided a display booth for the GWIM Project at which large-format, draft copies of the glacial and bedrock yield maps were displayed. Well drilling contractors were invited to scrutinize the maps and write edit suggestions directly on them. Twelve contractors made written comments on the maps. Anecdotal evidence confirms that this activity was very successful. Most of the contractors who stopped by the booth (45 – 50 individuals) regarded the GWIM Project and its draft products favorably to very favorably. No negative comments were made by those who stopped to discuss the project.

Two presentations were made to the Groundwater Conservation Advisory Council at their request. These occurred on September 30, 2004 at the MDNR's MacMullen Conference Center at Higgins Lake and on April 22, 2005 in Grand Rapids.

In addition to the monthly meetings with the technical advisory panel mentioned in Section 1.3, commencing in January 2005 a technical working group was formed to develop the details of the glacial and bedrock aquifer characterizations and assess the preliminary products. This group was composed of Brant Fisher and Joseph Lovato from the MDEQ, Howard Reeves from the USGS and Steve Miller and Dave Lusch from MSU. Initially, this workgroup met monthly, but in the June – August, 2005 period the group met more frequently, as needed, sometimes on a weekly basis.

1.6 Summary of Products and Recommendations

The data and methods used to compile the final maps and inventory items to comply with P.A. 148 are summarized in this report. This Technical Report, and its companion Executive Summary, are available on the project web site (gwmap.rsgis.msu.edu/), which is an important feature of this project. All the assembled data and analyses derived from the raw data are available on this site, in addition to the final maps required by the legislation.

The inventory and map products are available to end-users in three ways. Each of these provide for interactive viewing and use of the data at larger scales not possible with the small-scale maps provided in this report or the Executive Summary. The DEQ, Water Bureau web site will provide links and explanations of use for all three distribution mechanisms:

1. A web-based mapping site hosted by Remote Sensing and GIS Research and Outreach Services at MSU (gwmap.rsgis.msu.edu/). Some digital data are also available for download from this site.
2. Digital data provided on compact disc for use with the Map Image Viewer software (MIV), an easy-to-use GIS software package for viewing and analyzing spatial data. The Remote Sensing and GIS Research and Outreach Services group at MSU provides this mechanism. There is a charge for this service for users other than local health departments and the DEQ.
3. The digital data are also available for download through the State of Michigan, Center for Geographic Information (www.michigan.gov/cgi).

Section 32802 of P.A. 148 (Acts of 2003) specified that the "groundwater inventory and map" include the following items (a) through (h). These became the core product objectives of the Project. The various map products compiled under each objective are listed *in italic type*, below:

(a) **Location and water yielding capabilities of aquifers in the state** (Section 4.2)

4.2.1 *Glacial Deposits – Estimated Transmissivity*
Glacial Deposits – Estimated Yield
Glacial Deposits – Estimated Drawdown

4.2.2 *Bedrock Aquifers – Estimated Transmissivity*
Bedrock Aquifers – Estimated Yield
Bedrock Aquifers – Estimated Drawdown

(b) **Aquifer recharge rates in the state** (Section 4.3)
Estimated Recharge to Glacial Deposits

(c) **Static water levels of groundwater in the state** (Section 4.4)
Estimated Depth to the Water Table

(d) **Base flow of rivers and streams in the state** (Section 4.5)
Estimated Base Flow of Rivers

(e) **Conflict areas in the state (as defined by P.A. 177)** (Section 4.6)
Groundwater Use Conflicts

(f) **Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources that are identified on the natural features inventory** (Section 4.7)
Trout Lakes and Streams, and Groundwater Dependent Resources from the Michigan NFI

(g) **The location and pumping capacity of all registered industrial or processing facilities, all registered, non-agricultural irrigation facilities, and all public water supply systems that have the capacity to withdraw over 100,000 gallons of groundwater per day average in any consecutive 30-day period** (Section 4.8)
Non-agricultural Groundwater User by Type

(h) **Aggregate agricultural water use and consumptive use, by township** (Section 4.9)
Agricultural Water Use, by Township

In fulfillment of the requirement to "collect and compile groundwater data into a statewide groundwater inventory ..." the project searched the available literature for relevant theses, journal articles, abstracts, conference presentations/papers, and government documents that described groundwater characteristics anywhere in Michigan. This "statewide groundwater inventory" is available to the public through a web application described in Chapter 5.

1.7 Recommendations

There is still much to learn about the groundwater resources of Michigan and their stewardship. For this issue area, Michigan's number one priority should be the maintenance and enhancement of the maps and data compiled by the Groundwater Inventory and Map (GWIM) Project. The team strongly recommends the following as necessary steps to maintain, enhance, and expand upon this *initial* GWIM Project.

Simply stated, this project would not have been possible without the extensive electronic database of water well records, *Wellogic,* which is maintained by DEQ. The

Wellogic program is primarily supported by federal funding through the Clean Water Act, Section 106. As budgetary constraints continue to squeeze the DEQ, other Water Bureau programs are looking to this source of funding (Section 106) for support, thereby threatening the long-term viability of the *Wellogic* database and program. The success of future site-specific studies and other local groundwater protection efforts will also depend on a vibrant, up-to-date *Wellogic* database. Refinement of the groundwater yield estimates produced by the GWIM Project will require field mapping of glacial geology at local scales, additional characterization of the full thickness of glacial deposits, and many more hydraulic characterizations of aquifers in regions that currently are data poor.

1.7.1 Recommendations Concerning Database issues

- Continue to maintain and add documents to the GWIM.
- Continue to maintain *Wellogic* adding new well records in a timely fashion.
- Enter data from the scanned historic well records (~800,000 available) into *Wellogic*, prioritizing areas where electronic well records are scarce.
- Continue to provide outreach and technology transfer on the use and importance of *Wellogic*.
- Pursue consistency in water-use reporting requirements. Current inconsistencies include reporting either capacity or use, reporting use by facility or well, and reporting use aggregated by township.
- Develop a process to streamline the mapping of water use and provide tools to DEQ and MDA to simplify the mapping procedure as new data are submitted each year.

1.7.2 Recommendations Concerning Mapping issues

- Explore ways to obtain hydraulic characteristics of aquifers, especially in data-poor areas, with a priority on areas of potential future water resource development.
- Update the improved bedrock topography map and the improved thickness map of the glacial deposits that were created by this project. Much of the information required for this updating task was collected and scanned during the aquifer map and inventory project.

- Develop large-scale (i.e. local) 3-D maps identifying the major confined and unconfined aquifer zones in the glacial deposits. Such a task was considerably beyond the time-line and budget of this project.
- Support and expand the detailed glacial geology mapping of the Michigan Office of Geological Survey with a focus on relating this effort to groundwater resource management.

1.7.3 Recommendations Concerning Water Balance and Impact Data

- Maintain the existing groundwater-level monitoring program and expand it to include both background wells that provide information on the natural variability of water levels and wells in areas of active pumping to record induced changes. The network also should include wells in the major bedrock aquifers and in a variety of glacial settings.
- Study and report on the temporal trends in the existing groundwater-level data. This analysis would provide insight to areas of Michigan that are more or less sensitive to drought, and provide a water-use and climatological context to the reported static water levels.
- Expand surface-water gaging network to improve estimates of baseflow and recharge.
- Collect low-flow streamflow measurements for currently ungaged watersheds to confirm the baseflow estimates and provide additional data to improve these estimates.
- Research practical methods to link aquifer analyses, water-use information, and baseflow and recharge estimates to evaluate the ecological impact of future groundwater resource development.

Chapter 2 Data Sources

A major challenge of this study was the short timeframe for completion; therefore, the study had to rely primarily on existing data sources. The most important data sources used for the project are described in this section. The data sources are subdivided below into point data and areal data. For the development of an aquifer map, point data include well records and aquifer test analyses. These data are observations of the aquifer applicable to a limited area around the well. Point data provide information regarding the heterogeneity of the system and on the range of aquifer properties observed. Areal data include a variety of maps. By definition, maps homogenize the system to some degree depending on the scale of the map. Statewide maps may be too general to describe important differences on the county or township level, and they certainly do not capture the heterogeneity observed in the aquifer properties of glacial deposits. In this project, a combination of existing point and areal data is sought to provide the required information for quantifying groundwater-resource availability.

2.1 Point Data

2.1.1 *Wellogic* database

All water wells drilled in the State must be logged and the record must be filed with the county health department and MDEQ. The *Wellogic* system provides an electronic reporting process where drillers may submit the records electronically. The system has a defined set of lithologies helping to standardize the terminology used on the records. Use of the *Wellogic* system has created a database of water well records. MDEQ maintains the database and receives approximately 1500 new water well records per month. The database also includes records that were transcribed from paper records to digital form. In addition to the digital records in *Wellogic*, approximately 800,000 water well records, most from 1965-1999, were scanned and are available through the internet in adobe acrobat format. To provide information in areas of the State where *Wellogic* records were scarce, approximately 20,000 of the scanned records were entered into the *Wellogic* database as part of this project.

The *Wellogic* database has over 400,000 records of which approximately 290,000 records were used in this study. The water well records used have over 1.4 million reported lithologies. *Wellogic* stores the well record information in a structured query language (SQL) database. Data from the database are extracted with custom software to produce a shapefile (ERSI, 1998) containing data that summarizes the location and construction details for the well and an associated table listing the reported lithologies for the well. The information in the shapefile and table are associated by a unique identification number assigned to each record. These tables allow the information from the well records in the system to be readily displayed on a map and queried with Geographic Information System (GIS), database, or other software. The extraction is performed bi-weekly by MDEQ, and the resulting shapefile is made available to the public through the internet (MDIT, 2005a). Modifications and extensions to the extraction software developed for this project are discussed in Chapter 4.

2.1.2 Aquifer Test Analyses

MDEQ issues permits for the development of public water supplies including those using groundwater. Wells for public water supply are categorized into Type I, Type II and Type III wells. Type I wells provide year-round service to twenty-five or more persons in fifteen or more living units. An aquifer test is required to obtain a permit for wells for Type I systems. Aquifer-test analyses for Type I wells that were reviewed and approved by MDEQ were summarized in a database. The database, referred to in this project as the P-1 Database, provides a reliable source for aquifer-test analysis results for aquifers across the State. In addition to the Type I aquifer-test results, aquifer properties used for wellhead protection area (WHPA) delineations are provided in the P-1 database. These WHPA analyses have not been subjected to as thorough of a review and analysis as the Type I permit tests, but they are considered to be reasonably reliable.

2.1.3 Bedrock Aquifer Hydraulic Characteristics

As part of the U.S. Geological Survey Regional Aquifer Systems Analysis (RASA) program, older aquifer-tests performed for public water supply across the State and submitted as paper records to Michigan Department of Natural Resources were copied, transcribed to computerized files, and re-analyzed using the Ground Water Analysis Package (Dansby and Price, 1986; Mandle and Baltusis, unpublished analysis). The records from this analysis were examined and the well records for the test wells were searched in paper records, the *Wellogic* database, and the scanned water-well record compilation. Using information from the copied records, and well records when found, the location of the wells was recorded in a database along with the aquifer characteristics determined in the RASA study. This added 238 values to the P-1 and well-head protection database giving a total of 470 aquifer-test values for wells in the glacial deposits and 233 values for bedrock wells.

2.1.4 Other Aquifer Characterizations

The groundwater inventory and map includes a summary of groundwater-resources by county. While preparing these summaries, aquifer-test or specific capacity values given in reports were entered into a database. This database does not have the quality control on the aquifer-test analysis that the P-1 and RASA databases have, but it does provide additional estimates for aquifer characteristics. Typically, especially in older reports, the wells are reported using the township-range-quarter section approach. The values reported will be mapped to the center of the quarter-quarter section, or smallest geographic descriptor, given in the report.

2.1.5 Top of Bedrock Data

The final database for subsurface data is the oil and gas log database complied by Michigan Department of Natural Resources. There are approximately 53,000 entries in this database. While these logs typically do not provide information regarding the glacial deposits, they do provide information required to produce an improved bedrock topography map. Bedrock topography is important to estimate of the thickness of glacial deposits. This thickness is one factor that determines the amount of water in storage in the glacial deposits, and it also is one factor that must be considered when alternative water resources are sought to remedy or prevent ground-water conflicts. A draft revised bedrock elevation map was developed during this project using data from the oil and gas log database, water wells developed in the bedrock, and data derived from maps (R. Rieck, Western Illinois University, written communication, 2005). This data was used for mapping glacial yield to show areas were the glacial drift is less than 30 feet. A revised bedrock topography map is was not part of this scope of work for this project, and time did not permit completion in a final form. A revised map is needed and will be pursued in future.

2.1.6 Stream Gage Data

Two components of the inventory and map required by the legislation are estimates of baseflow of rivers and streams, and recharge to the groundwater system. Both of these requirements rely on stream-gaging-station data. The USGS provides this data yearly (for example, Blumer and others, 2003) and through the internet. The methods used to collect and analyze these data are described by Blumer and others (p. 1-34, 2003).

2.2 Areal Data

2.2.1 Bedrock Aquifer Characterizations

The RASA study provides a great deal of information on the Lower Peninsula of Michigan including a fresh-water/saline-water interface analysis (Westjohn and Weaver, 1996a), recharge estimate map (Holtschlag, 1996) and bedrock aquifer characteristics (Westjohn and others, 1994, Westjohn and Weaver, 1996b, Westjohn and Weaver, 1996c, Barton and others, 1996). Simulation results from a numerical model written for the RASA study (Hoaglund and others, 2002) may provide estimates of groundwater exchange between the glacial deposits and bedrock units and between bedrock aquifers. The RASA analysis was used extensively in the inventory and map of bedrock aquifers across the State.

2.2.2 Groundwater Availability

Twenter (1966a, 1966b) produced a pair of maps summarizing the general groundwater availability in glacial deposits and bedrock in Michigan. The map serves as a starting point for the updated inventory and map produced through this project. Unfortunately there is no associated documentation with these maps describing the background information on which they are based.

2.2.3 Aquifer Characteristics of the Glacial Drift

Western Michigan University (1981) produced an atlas of groundwater resources for Michigan. This atlas contains a map of glacial aquifer characterisitics (Plate 26). The atlas also provides an extensive bibliography. Plate 26 provides another generalized map that serves as a starting point for this project. It also may be used to compare the spatial patterns produced through the analysis of point data to test if general patterns noted on the Plate are evident in the point data. To facilitate the spatial comparison, this plate was digitized and the information stored in a shapefile (ESRI, 1998). The shapefile will be made available to the public as part of this project.

2.2.4 Hydrologic Provinces of Michigan

A third generalized statewide map of ground-water resources was compiled by Rheaume (1991). In this report, Michigan is subdivided into hydrologic provinces that may be useful in comparing spatial patterns produced through analysis of point data.

2.2.5 Glacial Geology

The glacial geology of the State was summarized in maps compiled by Farrand and Bell (1982a, 1982b). These maps are the latest update of a sequence of maps of the glacial geology of Michigan (see Chapter 3 for more detail). The map is readily available in GIS format. Thus, the polygons defining the different depositional environments described on the map can be easily manipulated and combined with point data in this study. As with all of the statewide maps listed, the scale of this map is small (1:500,000) and it may miss many important site specific features across the State. There also are areas where the textural or glacial-depositional classification, or the boundary between different classifications is disputed.

2.2.6 Bedrock Geology

The bedrock geology of the State has been summarized in maps compiled by Reed and Daniels (1987) and Milstein, R.L. (1987). The combination of these two maps (one for the Upper Peninsula and one for Lower Michigan) is readily available in GIS format from the Michigan Center For Geographic Information. This map was used as the major input to the bedrock aquifer delineation and characterization effort described in section 4.2.2.

2.2.7 Soils Data

The Natural Resources and Conservation Service (NRCS) has produced the State Soil Geographic (STATSGO) database by generalizing the detailed county-level, soil survey data. The mapping scale for STATSGO is 1:250,000, a level of mapping that is designed to be used for broad planning and management uses covering state, regional, and multi-state areas.

The base map used for STATSGO is the U.S. Geological Survey (USGS) 1:250,000 topographic quadrangles. The number of soil polygons per quadrangle map is between 100 and 400. The minimum area mapped is about 1,544 acres. Map unit delineations match at state boundaries.

Each STATSGO map unit is linked to the Soil Interpretations Record (SIR) attribute database. The attribute database gives the proportionate extent of the component soils and their properties for each map unit. An individual STATSGO map unit consists of up to 21 components. The Soil Interpretations Record database includes over 25 physical and chemical soil properties, interpretations, and productivity. Examples of information that can be queried from the database are available water capacity, soil reaction, salinity, flooding, water table, bedrock, and interpretations for engineering uses, cropland, woodland, rangeland, pastureland, wildlife, and recreation development.

The dominate soil texture for each STATSGO map unit in Michigan was determined to support the development of the new Glacial Landsystems map (see Chapter 3). This texture processing was based on the Michigan Soil Management Group approach (Mokma, Whiteside and Schneider, 1974) as presented in Appendix 8.1.

At a much more detailed level, NRCS also produces the Soil Survey Geographic (SSURGO) database. In Michigan, the SSURGO mapping scales generally range from 1:20,000 to 1:40,000. SSURGO is the most detailed level of soil mapping done by NRCS. The SSURGO digitizing duplicates the original county-level, soil survey maps. For the GWIM Project, the available SSURGO data in Michigan were used in the development of the map of the depth to the water table as detailed in section 4.4.2.

2.3 Educational and Bibliographic Information

In addition to data on aquifer characteristics, the GWIM Project assembled general informational material on groundwater and developed an extensive bibliography of groundwater reports for the State. Educational material was collected with input from the Groundwater Advisory Council and the MDEQ technical advisory panel. Many reports documenting groundwater resources within Michigan are older State of Michigan or U.S. Geological Survey reports that are difficult to obtain. As part of the inventory project, over 100 reports were scanned and made available in adobe acrobat (pdf) format on the Internet. Details of the bibliography and other inventory material are presented in Chapter 6.

Chapter 3 Landsystems

3.1 Introduction

From the very beginning of the GWIM Project, the team recognized the need for a geologic framework that could be used to regionalize the various data that were being derived from the *Wellogic* data base. This need derives both from depositional facies differences and from spatial variations in deposit thicknesses. For example, an outwash sand and gravel deposit in a short-lived glacial spillway will typically be thin, while that found in a proglacial outwash plain that received sediments for a much longer period will be thick. The Quaternary geology maps (Farrand and Bell, 1982a, 1982b) were proposed as the necessary geologic framework. However, knowing the limitations of these maps it was decided to improve upon them by blending their morphological information with lithological data from the STATSGO soil association data base using the glacial landsystems perspective.

Due to its location in the core of the most extensive area of continental glaciation in the United States, the glacial history of Michigan has been studied for more than a century. The most notable pioneer scientist to contribute to our understanding of the glacial landscapes of the state was Frank Leverett, who worked for the U.S. Geological Survey and was a professor of geology at the University of Michigan. Leverett authored several small-scale maps of the surficial geology of Michigan (Leverett, F., 1911, 1912, 1915, 1917, 1924). One of his students, Helen M. Martin, worked for many years at the Michigan Geological Survey and published maps on the surface formations of the State (Martin, 1955, 1957). The glacial geology map for Michigan that is currently used the most was published more than 20 years ago by Farrand and Bell (1982a, 1982b). One reason for its popularity is that it is available as a GIS shapefile from the State of Michigan. For most of Michigan, this map used the surface formation boundaries from Martin (1955, 1957) and added lithofacies information from the general soil maps that are part of the U.S. Department of Agriculture, Soil Conservation Service (USDA, SCS) [now named the Natural Resources Conservation Service] county soil surveys. These general soil maps are typically published at a scale of 1:190,080 and depict soil associations that have a distinct pattern of soils, relief and drainage. At the time Professor Farrand was compiling the Quaternary geology maps, none of these general soil maps were available in spatially referenced digital form (i.e. GIS data) and few had been edge-matched with adjoining counties. The most recent map of the glacial formations of Michigan (and the Upper Midwest) was published a decade ago (Soller, 1992).

In the early 1990s, the Natural Resources Conservation Service issued the State Soil Geographic Data Base (STATSGO) for Michigan (USDA, SCS, 1991), one of the three soil geographic data bases they maintain: the Soil Survey Geographic (SSURGO) data base, the State Soil Geographic (STATSGO) data base, and the National Soil Geographic (NATSGO) data base. The SSURGO data base provides the most detailed level of information and was designed primarily for farm and ranch, landowner/user, township or county natural resource planning and management. The STATSGO data base was designed primarily for regional, multistate, river basin, State and multicounty resource planning, management, and monitoring. Soil maps for STATSGO are compiled at a scale of 1:250,000 by generalizing the more detailed (SSURGO) soil survey maps where they exist. Where detailed soil survey maps are not available, data on geology, topography, vegetation, and climate are assembled. Soils of like areas are studied, and the probable classification and extent of the soils are determined. Map unit composition for a STATSGO map is determined by transecting or sampling areas on the more detailed maps and expanding the data statistically to characterize the whole map unit.

There were four geospatial processing steps needed to compile the new, statewide glacial landsystems map:

1. Reclassify the Quaternary geology maps (available in digital form) to extract just the surficial formations (i.e. moraine, till plain, outwash plain or lake plain).
2. Determine the dominant texture of the soil association polygons in the STATSGO data.
3. Using GIS overlay techniques, combine the surface formations from step 1 with the soils textures from step 2.
4. Reclassify the surface formation – soil texture data into glacial landsystems.

3.2 The Glacial Landsystems Approach

The landsystems approach is a holistic form of terrain evaluation, linking surface geomorphology and subsurface materials in a landscape context and relating them genetically to process-landform studies. The glacial landsystem approach was championed more than 20 years ago by Nick Eyles, a professor of Geology at the University of Toronto (Eyles, 1983). This approach has been successfully used for many years to characterize process-form relationships within a range of glacial environments. The classic division into subglacial, supraglacial and glaciated valley landsystems has developed a greater understanding of the relationships between glacial processes and the often complex morphology and sedimentology of formerly glaciated areas.

The most recent developments of the glacial landsystem concept (Evans, 2003) have stressed the complexity of glacial depositional environments and the fact that variability in landform-sediment assemblages is dictated not only by the location of deposition, but also by the style of glaciation – itself a function of climate, basement and surficial geology and topography. A wide range of glacial landsystems have been compiled for different ice masses and dynamics, acknowledging the complexity of glacial depositional systems and highlighting the fact that spatially coherent landform-sediment assemblages can be superimposed in a landscape and that glacial landscapes are just as much a palimpsest as any other terrain type.

The overall utility of the landsystems approach was summarized by Eyles (1983):

> *"Terrain evaluation is aimed at understanding the natural features of the landscape and, as a process, inevitably involves terrain classification by which the landscape is separated into natural units. Each constituent unit must be internally homogeneous and distinct from the others. Recognition of landscape units implies that there is a genetic relationship between landforms and the processes and materials involved in their development. The processes are mainly surface geological processes that have been active in the recent past, but these may be very different from the processes active at the present time. The materials are the superficial and solid deposits that crop out at the surface and immediately underlie it.*
>
> *The number of landscape units, or classes, must be reasonably small and three main types can be recognized within a hierarchical classification.*
>
> *A land element is the simplest part of the landscape and is for practical purposes uniform in form and material and is suited for mapping at large scales (e.g. a drumlin or kame). A land facet comprises one or more land elements grouped for practical purposes; it is part of a landscape which is reasonably homogeneous and distinct from the surrounding terrain. Land facets are suited to mapping at scales of 1:50,000 to 1:100,000 (e.g. a drumlin field or an outwash plain). A landsystem is a recurrent pattern of genetically linked land facets, suitable for mapping at scales of 1:250,000 to 1:1,000,000 (e.g. subglacial terrain where sediments and landforms of the landscape have been deposited at the base of the ice-sheet). An example would be a drumlin field flanked by an outwash plain and esker system.*
>
> *Each landsystem can be defined in terms of the sediment complexes underlying and, at the same time, controlling surface topography. The conditions at rockhead also*

vary from landsystem to landsystem. Although terrain evaluation is said to be concerned only with the uppermost few meters of the ground (Mitchell, 1973), the glacial landsystems which are considered here extend to bedrock regardless of depth.

The basic premise of the approach followed in this book is that if the landsystem can be identified from surface landforms, then it is possible to identify, in turn, the relevant subsurface conditions. As such, the approach has an important role in the initial desk-study phase of planning a variety of applied projects with the potential for saving time and, hence, money."

3.3 Reclassification of the Quaternary geology maps

The digital version of the Quaternary geology map of Michigan that combines both the Northern and Southern Peninsula maps (Farrand and Bell, 1982a, 1982b) is shown in Figure 3.1. The reclassification scheme used to isolate the surface formation information from the Quaternary geology map is shown in Table 3.1. The results of this reclassification are shown in Figure 3.2. Four legend items on the Quaternary geology map ("Peat and muck", "Postglacial alluvium", "Artificial fill" and "Exposed bedrock surfaces") are not glacial surface formations *per se* and were coded <None> in the revised data base. Two spatial edits were performed on the Quaternary geology map. All "Dune sand" polygons that did not share a boundary with the shoreline (i.e. inland dunes), as well as all "Water" polygons were flagged for removal. Using the *Eliminate* command in ArcGIS (ESRI, 2005), the spaces originally occupied by the "inland dunes" and "Water" polygons were filled with the attribute of the adjacent formation with the longest common boundary. The "water" polygons were removed in order to avoid a difficult

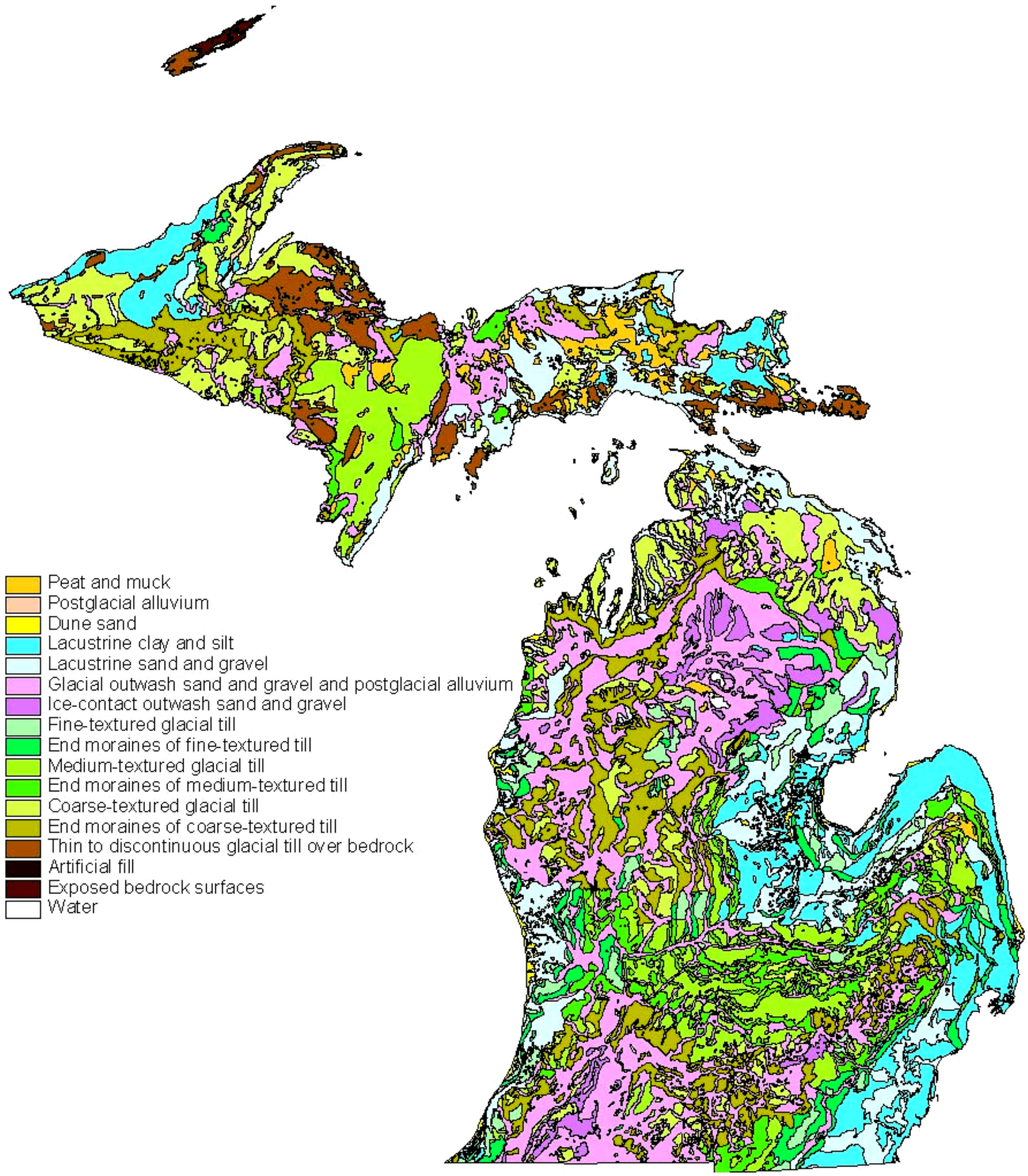

Figure 3.1. Quaternary geology of Michigan (Farrand and Bell, 1982a, 1982b).

sliver polygon problem so that the water class from the STATSGO data (1:250,000) could be used.

Table 3.1. Surface formation reclassification scheme.

Legend Items from Farrand and Bell, 1982a, 1982b	Reclassified Surface Formation
Peat and muck	None
Postglacial alluvium	None
Dune sand (spatially edited – see below)	Coastal dunes
Lacustrine clay and silt	Lake plain
Lacustrine sand and gravel	Lake plain
Glacial outwash sand and gravel and postglacial alluvium	Outwash plain
Ice-contact outwash sand and gravel	Moraine
Fine-textured glacial till	Till plain
End moraines of fine-textured till	Moraine
Medium-textured glacial till	Till plain
End moraines of medium-textured till	Moraine
Coarse-textured glacial till	Till plain
End moraines of coarse-textured till	Moraine
Thin to discontinuous glacial till over bedrock	Thin drift over bedrock
Artificial fill	None
Exposed bedrock surfaces	None
Water (eliminated – as described)	-

3.4 Dominant texture reclassification of the STATSGO data

The dominate soil texture and soil drainage class for each STATSGO data base record (i.e., map unit) were joined to the STATSGO soils map to develop a STATSGO soil texture map and a STATSGO drainage map. The processing was based on the Michigan Soil Management Group (Mokma, Whiteside and Schneider, 1974) and the component percent fields in the joined STATSGO data base using the procedure presented in Appendix 8.1. The mapping units of a detailed county soil survey identify the

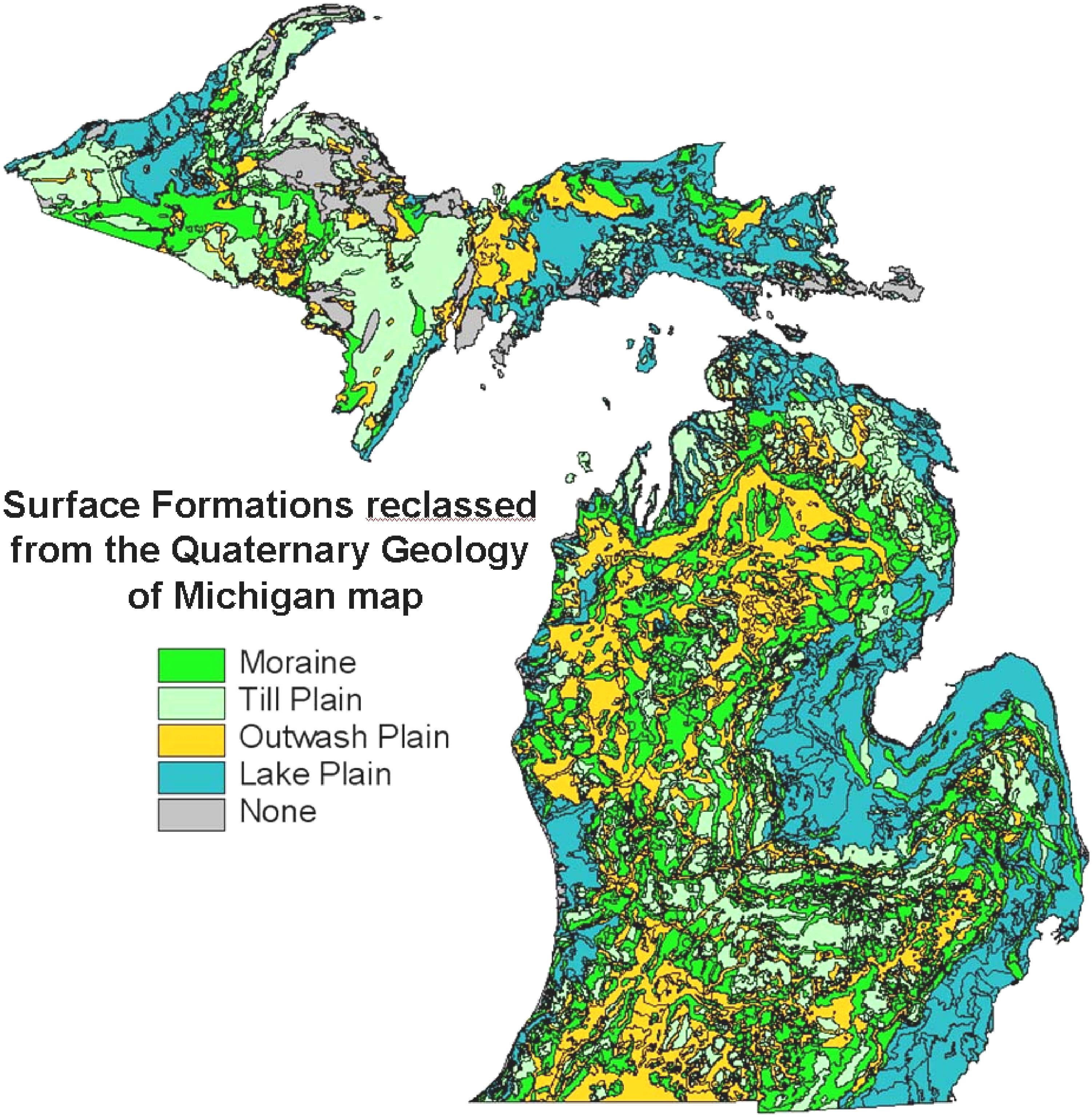

Figure 3.2. Surface formations reclassified from the Quaternary geology map.

predominant soil series in an area. Soil series differ from one another primarily on the basis of the thickness and arrangement of their horizons. Soil series can be aggregated according to the dominant texture of the entire profile (as opposed to the texture of the various horizons) as well as the natural drainage conditions to yield soil management groups. Table 3.2a shows the numeric coding scheme of the Michigan Soil Management Groups for texture, while Table 3.2b shows the alpha-codes assigned to the drainage classes within the Michigan Soil Management Groups.

The dominant soil texture for each STATSGO polygon, determined by the above process, is shown in Figure 3.3. It was decided that this map presented too much spatial diversity for the purposes of the groundwater mapping effort, so these detailed texture classes were grouped as shown in Figure 3.4. The vector polygons in this grouped texture map were dissolved on their texture group code to simplify the map.

3.5 Reclassify the surface formation – soil texture data into glacial landsystems.

Using GIS overlay techniques, the surface formations extracted from the quaternary geology map (section 3.3) were combined with the soils texture groups reclassified from the STATSGO soil data (section 3.4). The result of this overlay analysis is shown in Figure 3.5. In a final processing step, after concatenating the surface formation – soil texture data they were grouped into glacial landsystems as shown in Table 3.6. The final glacial landsystems map (Figure 3.6) was created using the *Dissolve* command in ArcGIS on the “Ldsystem” field.

Table 3.2a: Soil texture component of the Michigan Soil Management Groups.

Symbol	Description
0	Fine Clay (over 60%)
1	Clay (40-60%)
1.5	Clay loam and silty clay loam
2.5	Loam and silt loam
3/1	Sandy loam, 14-40”, over clay
3/2	Sandy loam, 20-40”, over loam to silty clay loam
3	Sandy loam
3/5	Sandy loam, 20-40”, over sand and gravel
4/1	Loamy sand, 14-40”, over clay
4/2	Loamy sand, 20-40”, over loam to silty clay loam
4	Loamy sand
5/2	Sand to loamy sand, 40-60”, over loam to clay
5	Sand with moderate to strong subsoil development
5.3	Sand with minimal subsoil development
5.7	Sand with little or no subsoil development
G	Gravelly or stony loamy sand to loam
L	Alluvial or Lowland Areas
L-2	Alluvial or Lowland Areas, Loamy
L-4	Alluvial or Lowland Areas, Sandy
m	Marl
R	Bedrock, less than 20”
2/R	Loam, 20-40”, over bedrock
3/R	Sandy loam, 20-40”, over bedrock
4/R	Sand to loamy sand, 20-40”, over bedrock
M	Organic Soils

Table 3.2b. Drainage class component of the Michigan Soil Management Groups.

Symbol	Description
a	Well and Moderately Well Drained
b	Somewhat Poorly Drained
c	Poorly and Very Poorly Drained
c	Organic Soils (M) Very Poorly Drained 16-51” thick
c	Organic Soils (M) Very Poorly Drained over 51” thick
bc	Poorly Drained

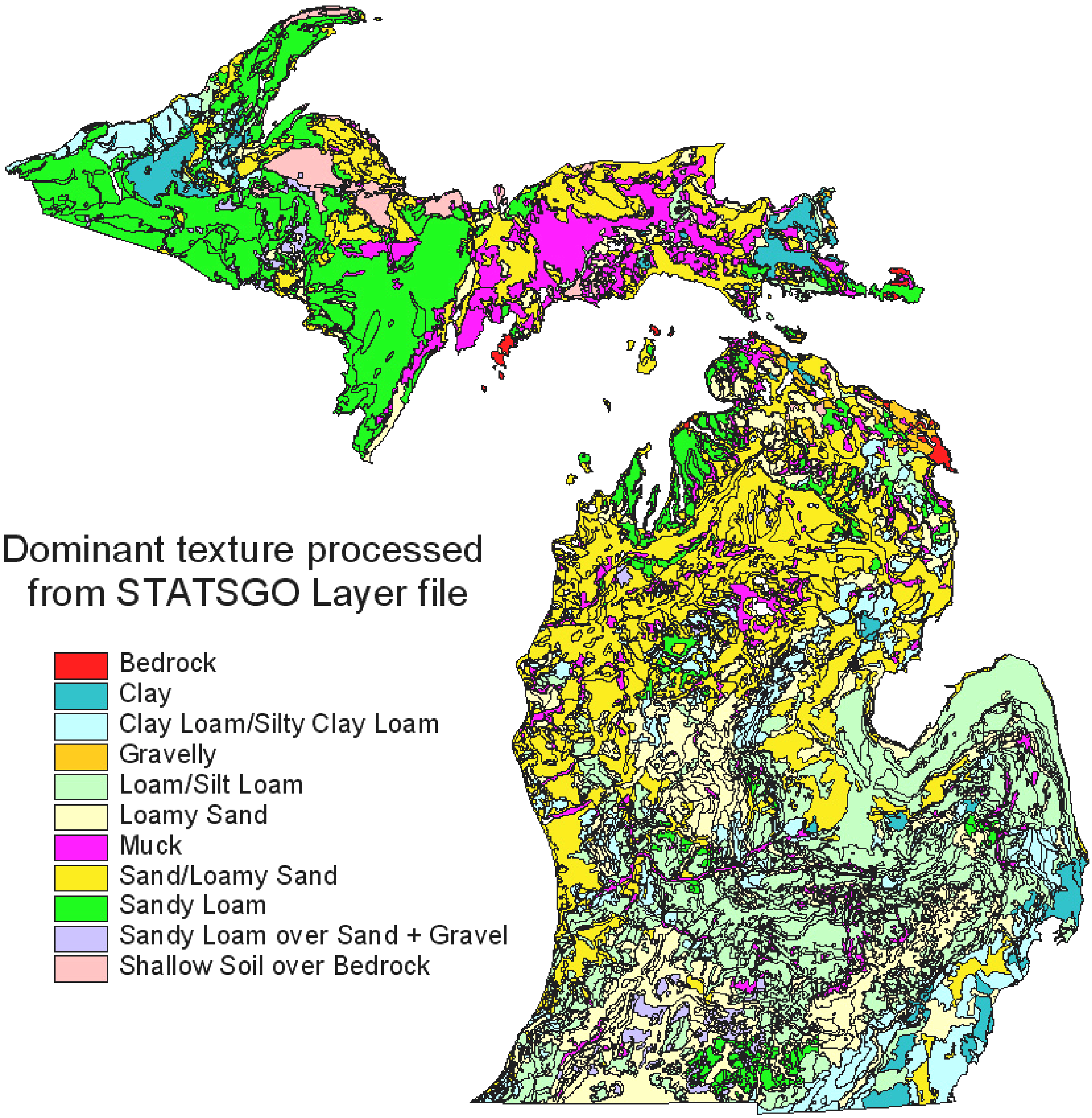

Figure 3.3. The dominant soil texture for each STATSGO polygon.

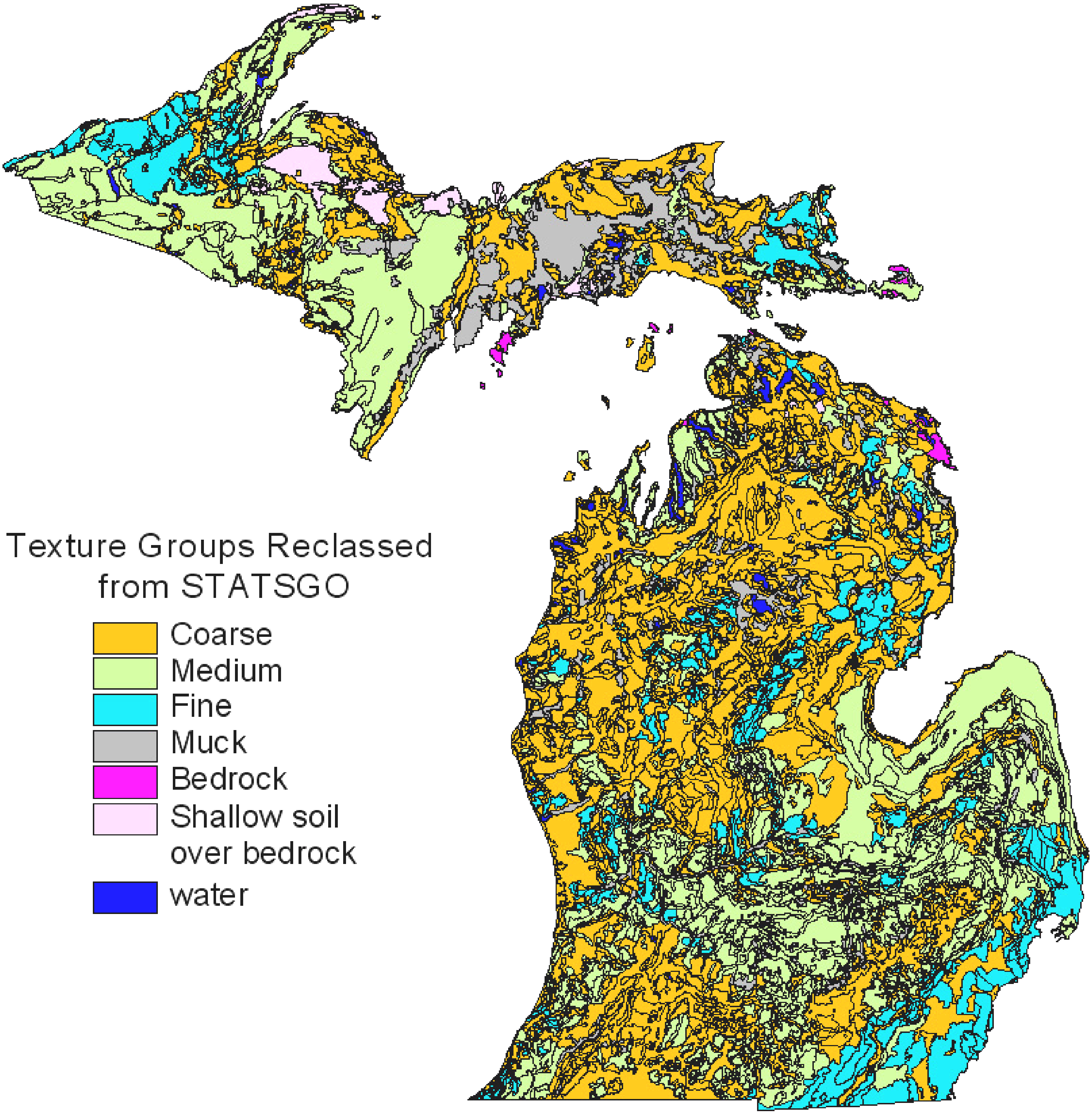

Figure 3.4. Grouped dominant soil textures from STATSGO.

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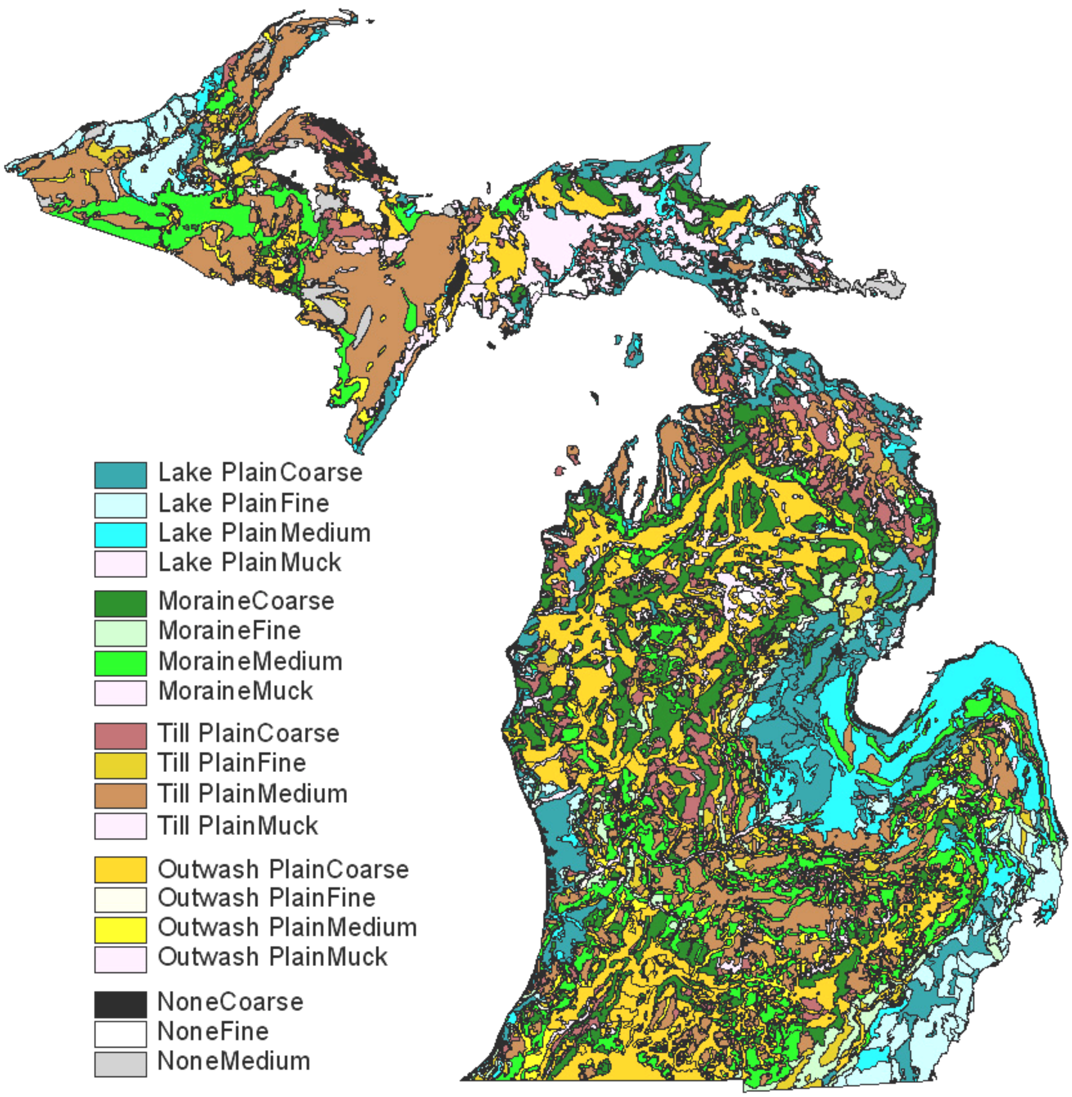
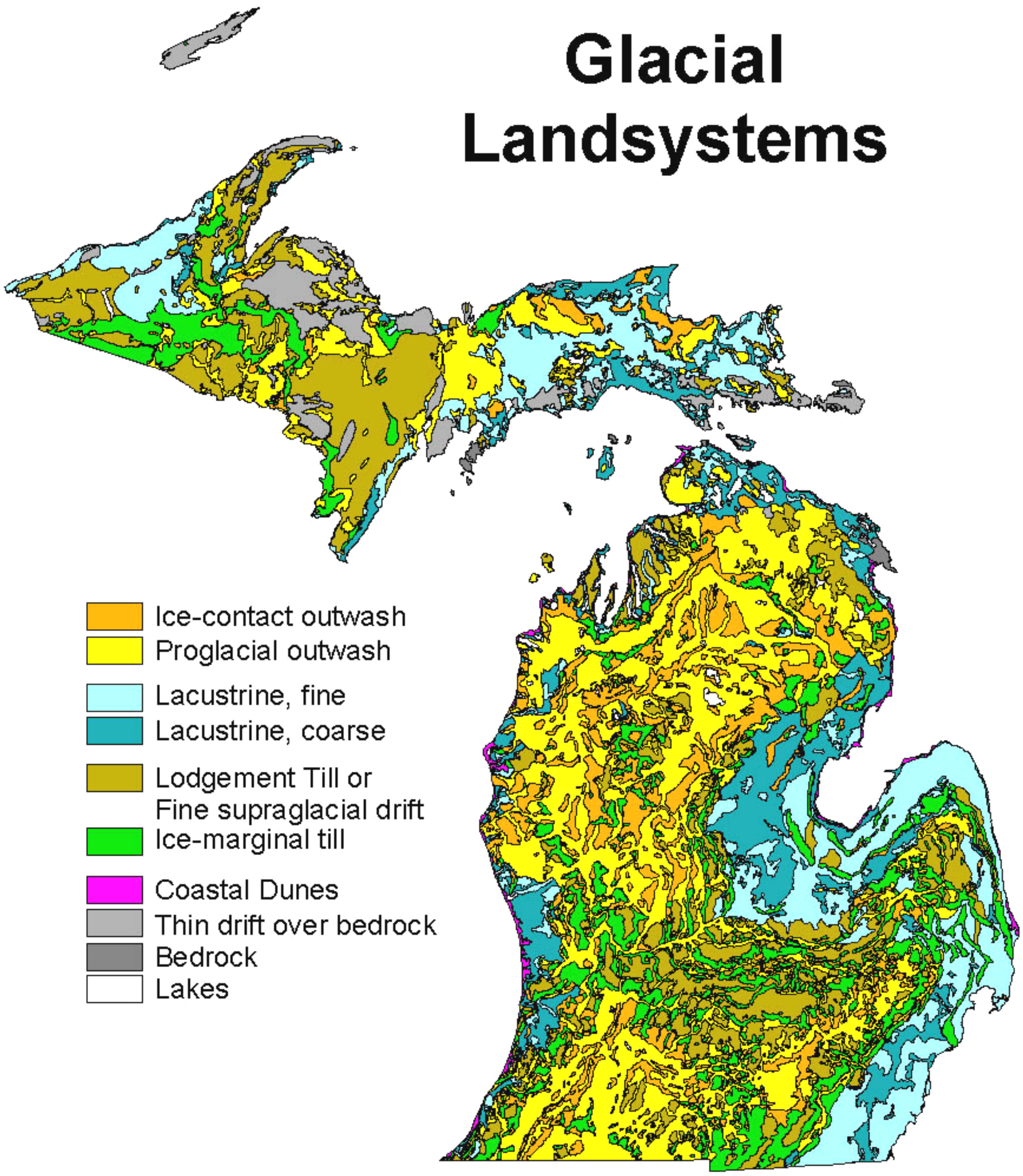


Figure 3.5. GIS overlay combination of surface formations and grouped soil textures.

Table 3.6. Relationship between surface formation – soil texture classes and glacial landsystems.

Surface formation – soil texture class	*Glacial Landsystem*
Moraine - Coarse	Ice-contact Outwash
Moraine - Medium	Ice-marginal Till
Moraine - Fine	Ice-marginal Till
Moraine - Muck	Ice-marginal Till
Moraine - Shallow Soil Over Bedrock	Ice-marginal Till
Lake Plain - Coarse	Lacustrine Coarse
Lake Plain - Medium	Lacustrine Fine
Lake Plain - Fine	Lacustrine Fine
Lake Plain - Muck	Lacustrine Fine
Till Plain - Medium	Lodgement Till or Fine Supraglacial Drift
Till Plain - Fine	Lodgement Till or Fine Supraglacial Drift
Till Plain - Muck	Lodgement Till or Fine Supraglacial Drift
Till Plain - Coarse	Proglacial Outwash
Outwash Plain - Coarse	Proglacial Outwash
Outwash Plain - Medium	Proglacial Outwash
Outwash Plain - Fine	Proglacial Outwash
Outwash Plain - Muck	Proglacial Outwash
Outwash Plain - Shallow Soil Over Bedrock	Proglacial Outwash
Dune Sand	Coastal Dunes
Thin to Discontinuous Glacial Till Over Bedrock – "Any Soil Texture Class"	Thin Drift over Bedrock
Lake Plain - Shallow Soil Over Bedrock	Thin Drift over Bedrock
Till Plain - Shallow Soil Over Bedrock	Thin Drift over Bedrock
"Any Surface Formation" - Bedrock	Bedrock



Chapter 3 Figure 3.6. Glacial Landsystems of Michigan.

Chapter 4 Aquifer Map Required Elements

4.1 Introduction

Public Act 148, Section 32802 (Michigan, 2003) required MDEQ to create a groundwater inventory and map that includes the following specific requirements:

(a) Location and water yielding capabilities of aquifers in the state.

(b) Aquifer recharge rates in the state, if available to the department.

(c) Static water levels of groundwater in the state.

(d) Base flow of rivers and streams in the state.

(e) Conflict areas in the state.

(f) Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources that are identified on the natural features inventory.

(g) The location and pumping capacity of all of the following:

  i. Industrial or processing facilities registered under section 32705 that withdraw groundwater.

  ii. Irrigation facilities registered under section 32705 that withdraw groundwater.

  iii. Public water supply systems that have the capacity to withdraw over 100,000 gallons of groundwater per day average in any consecutive 30-day period.

(h) Aggregate agricultural water use and consumptive use, by township.

This Chapter details the efforts to meet these eight requirements. Limitations of the information collected for each requirement will be discussed. The description of the aquifer yield maps provides a great deal of information on the final methods used to develop the maps. Several other methods that were tested and found to be unsatisfactory for this project are described in the Appendices of this report.

4.2 (§a) Location and water-yielding capabilities of aquifers in the State

This requirement is very challenging owing to difficulties in determining the boundaries of the numerous glacial aquifers and in quantifying the water-yielding capability of any aquifer (glacial or bedrock). To meet these challenges, the water-yielding capability, henceforth referred to as yield, from the glacial deposits that cover most of Michigan was investigated separately from the yield of bedrock aquifers. Although there is important heterogeneity at local scales, the general configuration of the various bedrock aquifers in Michigan is better known compared to aquifers within glacial deposits (Westjohn and Weaver, 1996b, Westjohn and Weaver, 1996c, Barton and others, 1994).

Yield from either glacial deposits or bedrock aquifers was mapped as the estimated hypothetical pumping rate that would cause a fifty-percent decrease in water level at a given location. This fifty-percent value was selected to account for well efficiency, which reflects the true behavior of a well in the field compared to the theoretical behavior of a well in the design equations. In addition to examining the behavior of the aquifer in response to a hypothetical withdrawal, a second map for each aquifer system (i.e., glacial *vs.* bedrock) was generated to show the estimated change in water level in the aquifer 500 ft from a hypothetical withdrawal at the estimated yield rate after 100 days. This second map allows the public, MDEQ, and those considering installing a high-capacity well to consider the general impact of groundwater withdrawal on neighboring wells. The map illustrates the general response to single-well, high-capacity groundwater withdrawal in different areas of the State; it should **not** be used for design. A site-specific analysis of both aquifer yield and the impact of a proposed high-capacity well on neighboring wells should always be performed to ensure that the proposed well will produce the desired quantity of water and that effects on the aquifer and neighboring wells are appropriately managed.

4.2.1 Glacial Deposits

In many areas in the Michigan, glacial deposits are extremely heterogeneous due to the complex depositional environments associated with glaciation, and most glacial aquifers are not identified because such identification requires costly and time-consuming site-specific studies. Therefore, the horizontal and vertical continuity of most glacial aquifers in Michigan is unknown. For the glacial aquifer maps in the GWIM Project, glacial deposits were considered to be a single resource and treated as one complex aquifer. For much of the State, we recognized that the most probable configuration of a layered system with several aquifers separated by generally leaky aquitards was difficult to identify. Instead of focusing on individual aquifer units, as would be required for a contaminant transport investigation, for instance, the yield from the thickness of glacial deposits typically used in water resource development was characterized for the purpose of estimating the water-resource potential of the glacial deposits.

Analysis of the hydrogeologic properties for the glacial aquifers in Michigan using the data sources outlined in Chapter 2 is complicated by several factors: natural heterogeneity of the glacial deposits, variability in the detail provided in water well records, errors and bias in all data sources, and scale issues. Effective groundwater management will require both accurate estimates of hydrogeologic properties and identification of areas in Michigan where more data are needed in order to sufficiently characterize the glacial aquifer. Eight different approaches were evaluated to assess the ability of each to characterize the glacial aquifer using available data. Ultimately, the methods linked directly to estimating and extrapolating the effective hydraulic conductivity of the saturated thickness are the ones that were adopted.

4.2.1.1 Percent Aquifer and Drift Index

The *Wellogic* database was used directly to construct generalized maps showing potential aquifers across the State. Previous work done by MDEQ in the Source Water Assessment Program (Michigan Department of Environmental Quality, 2004) classified the various lithologies into four groups: aquifer (AQ), marginal aquifer (MAQ), partially confining material (PCM), and confining material (CM). This attribute is reported in the AQTYPE (aquifer type) field in the *Wellogic* database extracted for the user. A second lithology classification that uses both the lithology and any secondary modifier is also derived. For example, if the primary lithology SAND is modified by WITH CLAY, then the class for that layer is assigned as marginal aquifer rather than aquifer. These more specific lithology classes are stored in the MAQTYPE (modified aquifer type) field. In addition to the AQ, MAQ, PCM and CM codes, a fifth class (NA) is also assigned for lithology entries that could not be classified (i.e., Lithology Unknown, Unidentified Consolidated Formation, etc.). Examination of the lithology file reveals that less than six percent of the 1.4 million reported lithology entries had a lithology modifier that reclassified the entry. See Table 8.8.1 in the Appendices of this report for the classification assignment for each lithology in *Wellogic*.

To facilitate mapping and to allow for spatial interpolation between water well record locations, an index, designated as the Drift Index (DI), was developed that summarized the amount of aquifer material reported in a well record (“drift” is a general term used for all types of glacial deposits (Foster, 1983)). This index quantifies the percent aquifer in the glacial deposits on the basis of the aquifer type classification described above. The Drift Index is calculated as follows:

$$DI = \frac{3*T_{AQ} + 2*T_{MAQ} + T_{PCM}}{T_t} \qquad \textbf{(4.2.1)}$$

Where: T_a is the summed thickness of class *a* (AQ, MAQ, PCM)

T_t is the total thickness.

DI was only computed for wells where less than 25 percent of the logged interval was classified as NA. Note that confining material (CM) does not contribute to the drift index. The DI was mapped statewide by interpolating the values computed from the *Wellogic* records using ordinary Kriging onto a 1000 m x 1000 m grid (Figure 4.2.1). The importance of this approach is that it shows agreement between the general spatial patterns mapped on Plate 26, Aquifer Characteristics of the Glacial Drift, of the Hydrogeologic Atlas of Michigan (Western Michigan University, 1981), but it is based on actual lithologic data from the *Wellogic* database. As will be shown in subsequent discussion, areas of high transmissivity are exhibited by DI values ≥ 2.4 and regions of low transmissivity have DI values ≤ 0.8. The Drift Index method is a statewide approach that can be applied in a consistent fashion to lithologic descriptions on the water-well records in the *Wellogic* database. **The general agreement between these point data and the qualitative glacial aquifer map supports the use of the *Wellogic* database to generate estimates of aquifer properties.** Within this general agreement, however, the information in the *Wellogic* database exhibits significant local-scale heterogeneity in many places across Michigan. A major challenge for this project was to develop interpretation tools that detected and communicated this spatial heterogeneity without reporting such a large range of potential values that the analysis becomes trivial.

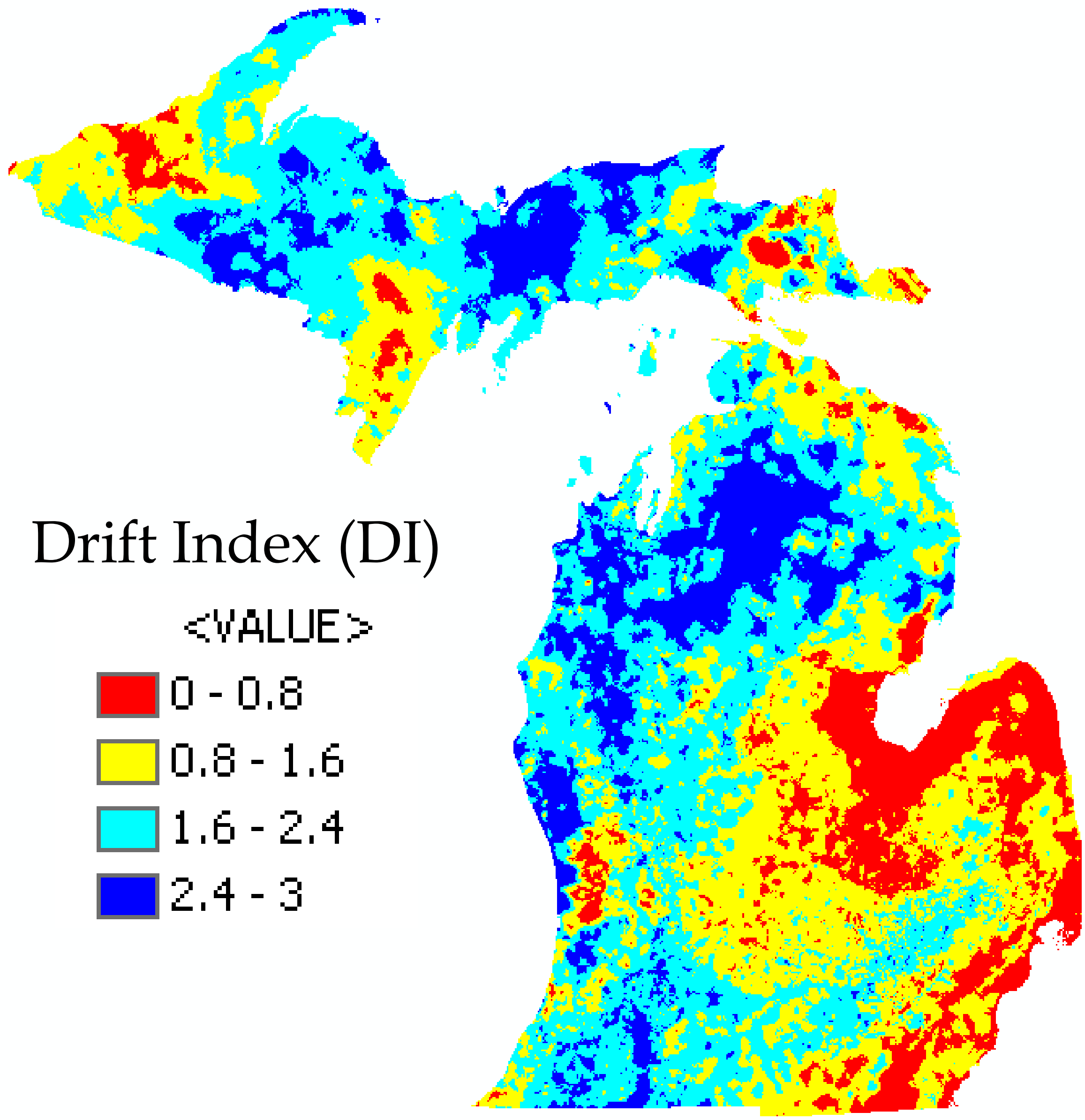


Figure 4.2.1. Interpolated Drift Index values. DI near zero indicates that the glacial deposits are dominated by clay and are likely to be poor aquifers. DI near 3.0 indicates that the glacial deposits are dominated by aquifer materials.

The extraction program (see Section 2.1) that converts from the *Wellogic* database to a shapefile (ESRI, 1998) adds 65 fields that calculate the DI by selected depth increments across the saturated thickness for intervals that had sufficient lithologic information. The depth increments computed are:

0 – 20 ft; 21 – 40 ft; 41 – 60 ft; 61 – 80 ft; 81 – 100 ft; 101 – 125 ft; 126 – 150 ft; 151 – 200 ft; ... 401 – 450 ft.

This method provides a means to analyze the lithology data at depth and can be used to identify areas where, based upon a change in the DI, the surficial lithology is not representative of deeper glacial deposits. An example map using these data is shown as Figure 4.2.2. This map shows the difference between the overall DI and the DI for the uppermost twenty feet ($DI_{0\text{-}20}$) of the water well record. The negative values in this figure indicate that the upper twenty feet are dominated by coarse-texture drift and are underlain by finer-texture material at depth. Positive values indicate that the upper twenty feet tends to have less aquifer material than the entire record. This latter situation arises where fine-texture deposits near the surface overlie coarse-texture material at depth. Values near zero indicate that the hydraulic character of the deposits, which are indicated broadly by the drift index, are constant with depth.

To characterize drift texture with depth, a Trend Index (TI) was developed. TI reports the ***change*** in DI with each successive layer (Layer 1 → Layer 2 → Layer 3) [*0 – 20' → 21' – 40' → 41' – 60'*] paying particular attention to DI changes equal or greater than one unit. A positive TI indicates that the drift becomes more coarse with depth, while a negative TI shows that drift texture fines with depth.

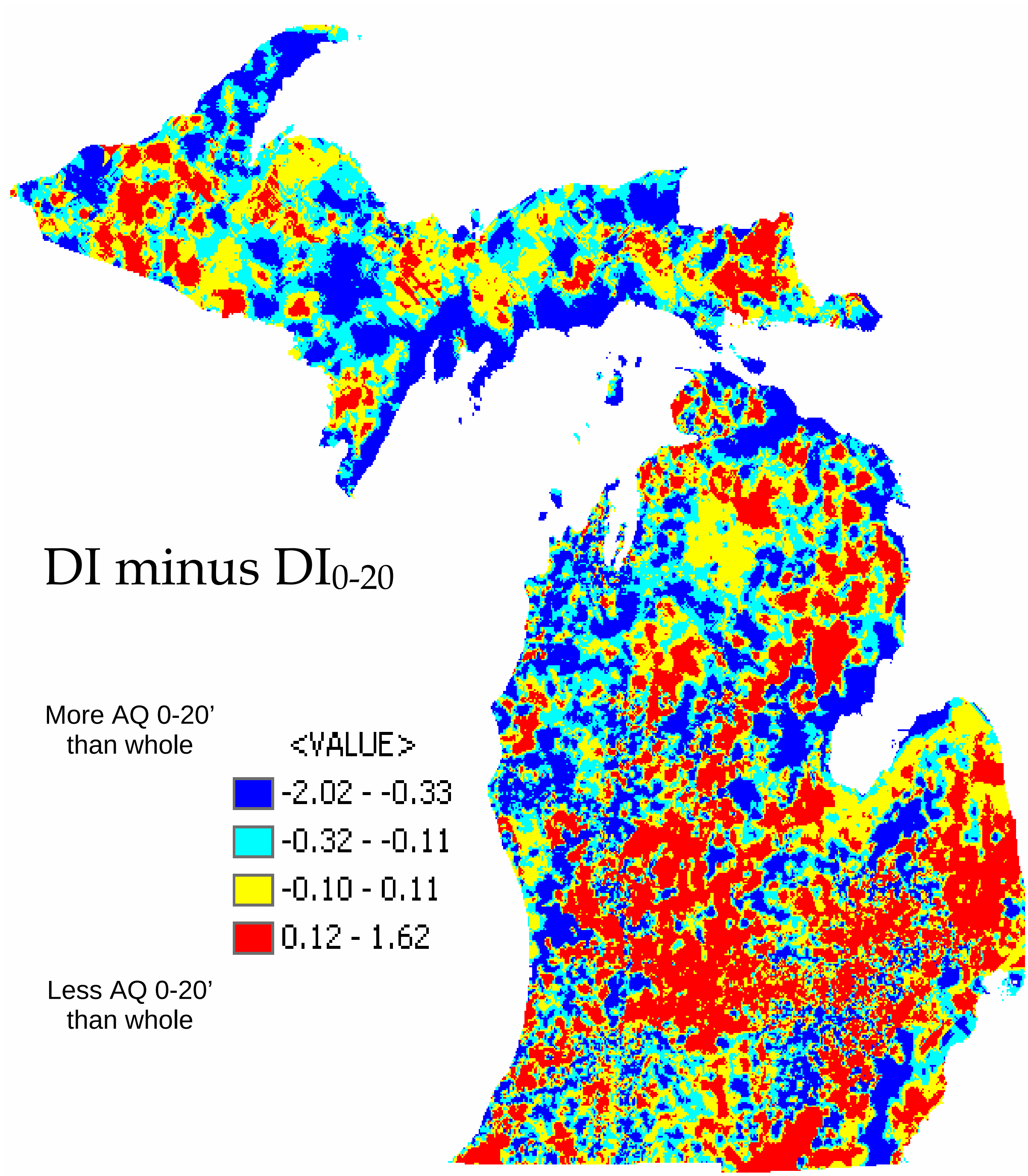


Figure 4.2.2. The shallow Drift Index difference. The DI for the entire thickness reported in the well record minus the DI for uppermost 20 feet of the well record. Positive differences indicate less aquifer material in the upper 20 feet, while negative differences indicate more aquifer material in the upper twenty feet. Aquifer material is defined in Table 8.8.1.

Disadvantages of the DI approach include the potential sacrifice in detail caused by classifying all lithologies into four classes and the inability to distinguish the continuity of aquifer layers. The DI method was replaced by the procedure used to estimate the equivalent hydraulic conductivity. However, the Trend Index data were used in the conductivity estimation method, as will be discussed below.

4.2.1.2Drift Index by Landsystem

The distribution of DI values that lie within each landsystem is summarized in Figure 4.2.3. This plot reveals that Drift Index varies by landsystem in a predictable fashion. The median DI for the lacustrine fine landsystem is statistically lower, to the 95% confidence level, than the median DI values of the other landsystems. The pattern of median DI values by landsystem follows the expected sequence in which the lowest DI values are associated with landsystems in which aquifer characteristics are expected to be poor, while the highest DI values are found in those landsystems where better aquifers are expected. The observed sequence in order of increasing median DI value is lacustrine fine, lodgement till or supraglacial drift, ice-marginal till, lacustrine coarse, ice-contact outwash, proglacial outwash, and coastal dunes. Note, however, the scatter observed for each landsystem - the entire DI range is observed in every landsystem.

Histograms of the DI values by landsystem (Figures 4.2.4 - 4.2.10) more fully present the data that underlies Figure 4.2.3. Each histogram has a significant proportion of well records that produced a DI value close to 3. In any landsystem there may be shallow wells that penetrate a surficial aquifer for almost the entire length of the well.

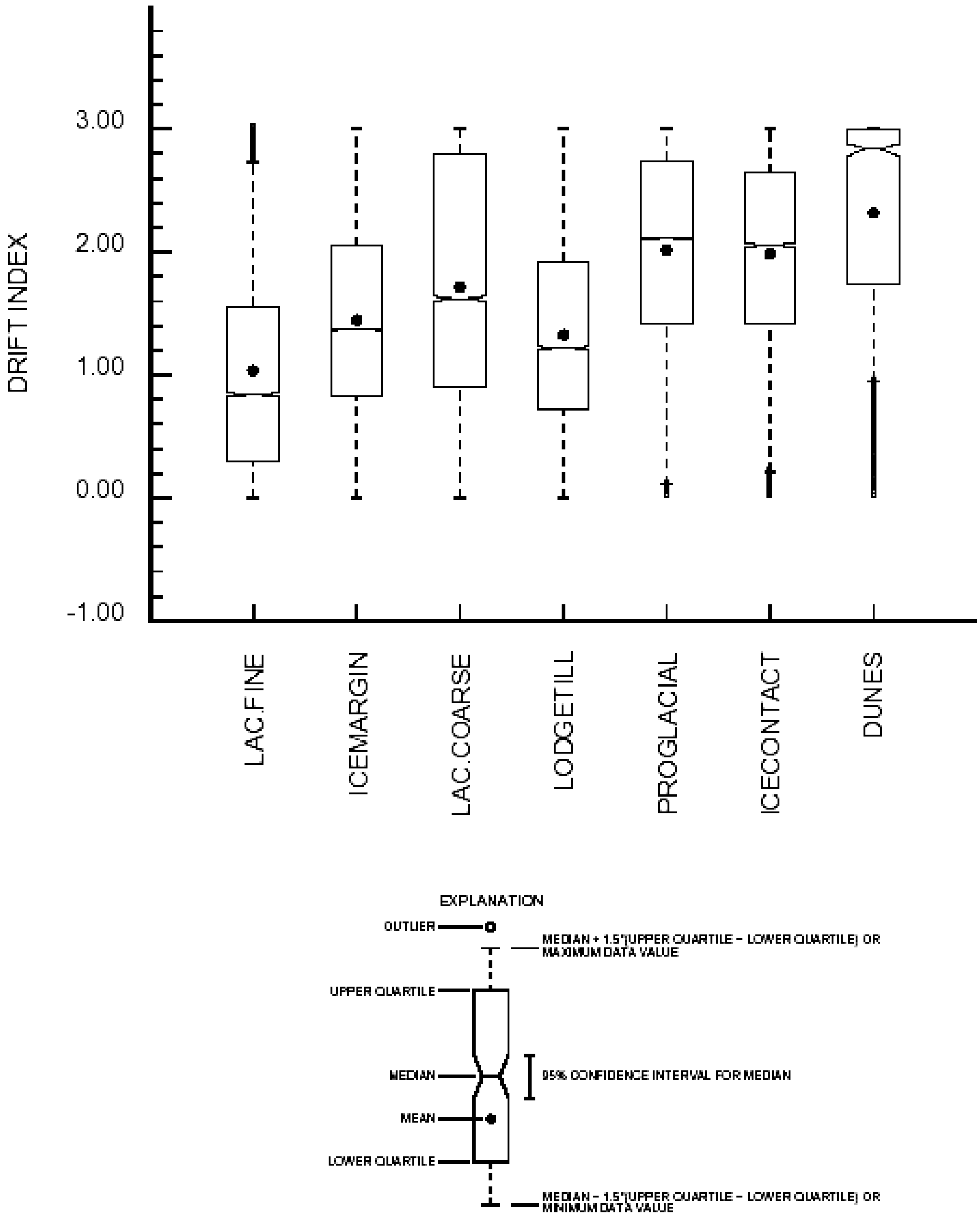


Figure 4.2.3. Distribution of Drift Index values within each landsystem depicting the mean, median, 95% confidence interval around the median, the upper and lower quartiles, and outliers beyond median ± (1.5*(upper - lower quartile difference)).

Even in depositional environments where continuous aquifers are not expected, there may be isolated sand and gravel deposits near the surface that may provide water for residential wells. Examination of the distribution of the remaining classifications in the histograms reveals interesting patterns. The coastal dunes landsystem has the fewest number of well records, and, although there is scatter across the entire range of DI values, the Drift Index distribution for coastal dunes is clearly dominated by DI values near 3 (Figure 4.2.10). The lacustrine fine, lodgement till or fine supraglacial and ice-marginal till landsystems (Figures 4.2.4 - 4.2.6) all show modal DI values near 1.0, indicating that either the well records are dominated by partially confining material or the records have a mixture of lithologies with a significant proportion of low-value confining material. An examination of the well records revealed that the latter situation dominated: many well records note substantial thicknesses of clay and a relatively low proportion of sand and gravel. The lacustrine fine landsystem is dominated by water well records with a Drift Index of zero, implying that no aquifer material was encountered in the drift portion of the record. Not surprisingly, such wells are typically completed in bedrock.

Figures 4.2.4 - 4.2.10 also present the semivariogram of Drift Index values for each landsystem. The semivariogram is a statistical method used to test for spatial structure of data (Chilès and Delfiner, 1999, p. 45-57). The semivariogram is developed by graphing the squared difference of pairs of samples separated by a given distance. In this case the difference between the DI of well pairs is used. If the Drift Index in a particular landsystem is completely uniform, the value of the semivariogram would be zero for every separation distance. If the Drift Index varies randomly within a landsystem, the plot versus distance would be constant and equal to the variance of the Drift Index values. Typically, the semivariogram is curved and starts at or near zero at small separation distances and increases to a plateau at larger separation distances. The plateau value is referred to as the sill and reflects the variance in the samples. The separation distance where the semivariogram reaches the sill is referred to as the range. If there is spatial correlation in the data, the range indicates the distance that correlation is expected. A sample does not provide any information to estimate values beyond the range of the semivariogram. If the data do not imply that the value of the semivariogram is zero at zero separation distance, then there may be errors in the measurement or variation in the system at distances smaller than the scale of the measurements (Ch ilès and Delfiner, 1999). The value of the semivariogram at zero separation distance is referred to as the nugget.

Figure 4.2.11 summarizes all the semivariograms by landsystem. At distances less than 2000 feet, the uncertainty in an estimated Drift Index value based on neighboring sampled points is less than the uncertainty at a point greater than 2000 ft away. The semivariograms for ice-contact and lodgement till landsystems have the highest sill values indicating the greatest variance in DI for the wells in these landsystems. The semivariogram for the dunes landsystem is fairly flat and indicates little spatial structure in the DI for this landsystem. The semivariograms for the rest of the landsystems show some curvature indicating some spatial structure. Because of this spatial structure, the DI for a well can be used to estimate the value of DI near the well. The nugget values for all systems, however, are fairly high compared to the sill. Therefore, the estimate near the well will have uncertainty almost as great as the variance in the DI dataset for the landsystem. DI differences between wells spaced close together arise from both how individual drillers report lithologies and the spatial heterogeneity of glacial deposits at scales small compared to the distance between most well pairs.

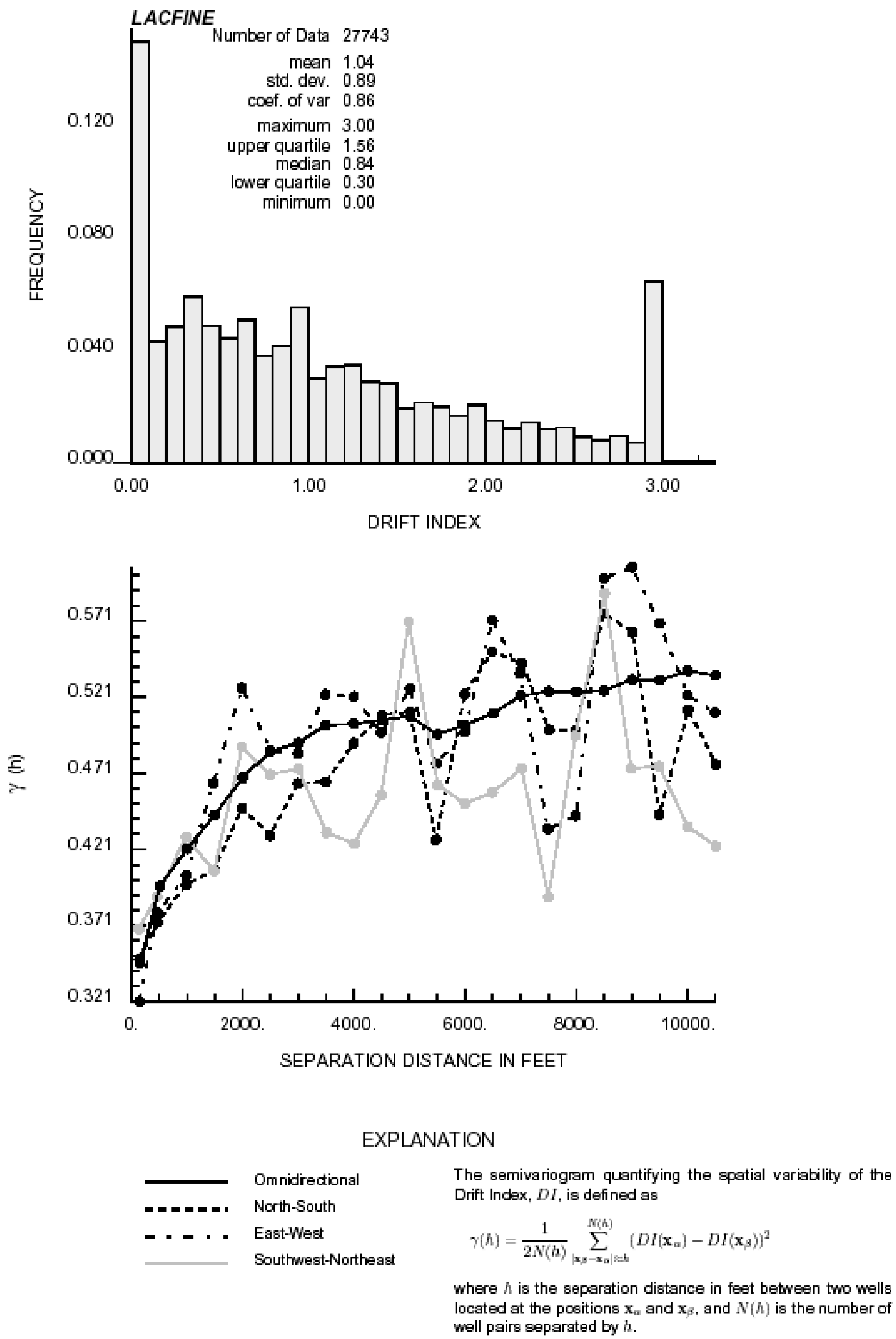


Figure 4.2.4. Histogram and semivariograms of Drift Index values for the Lacustrine Fine Landsystem.

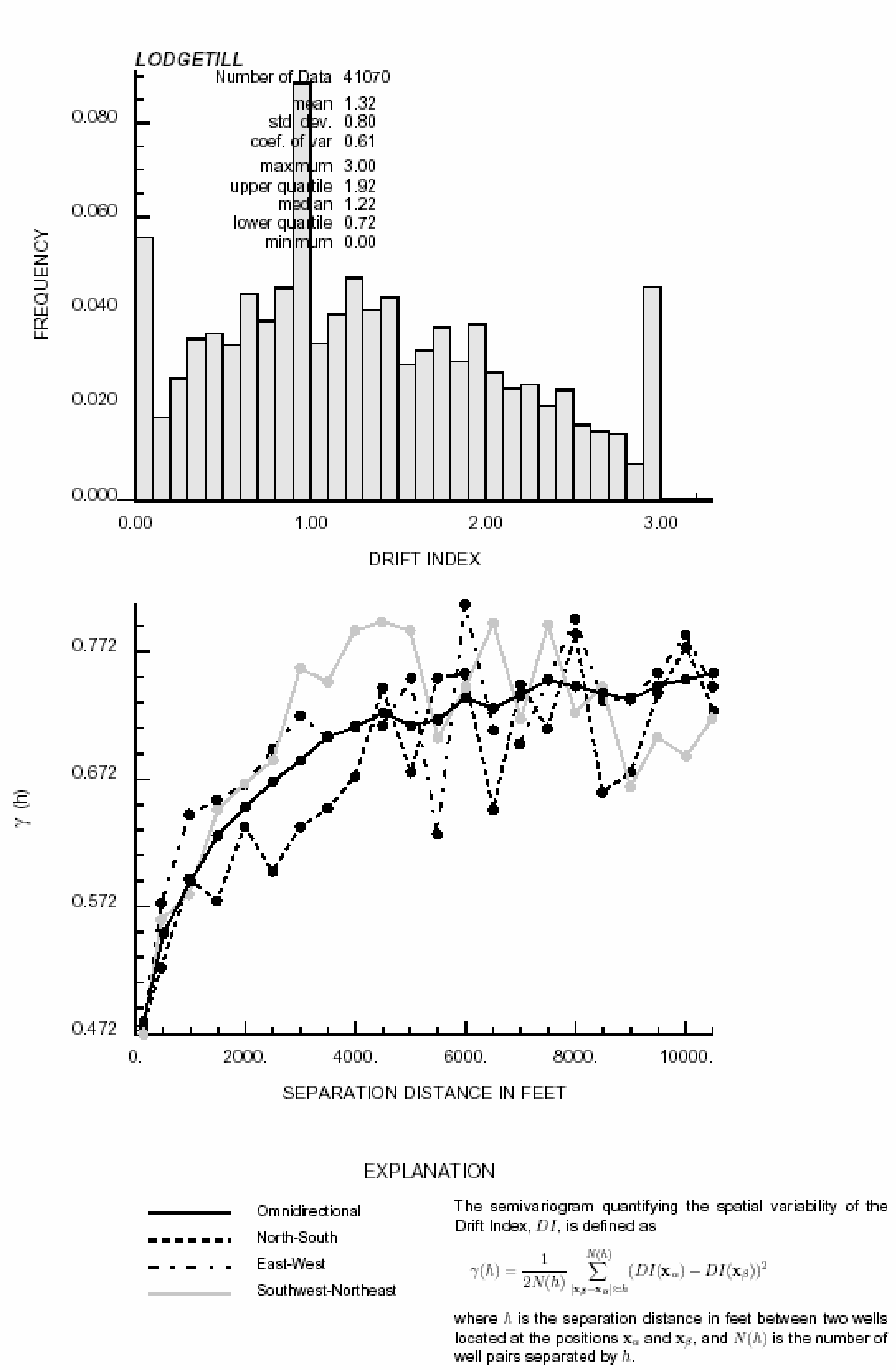


Figure 4.2.5. Histogram and semivariograms of Drift Index values for the Lodgement Till or Supraglacial Drift Landsystem.

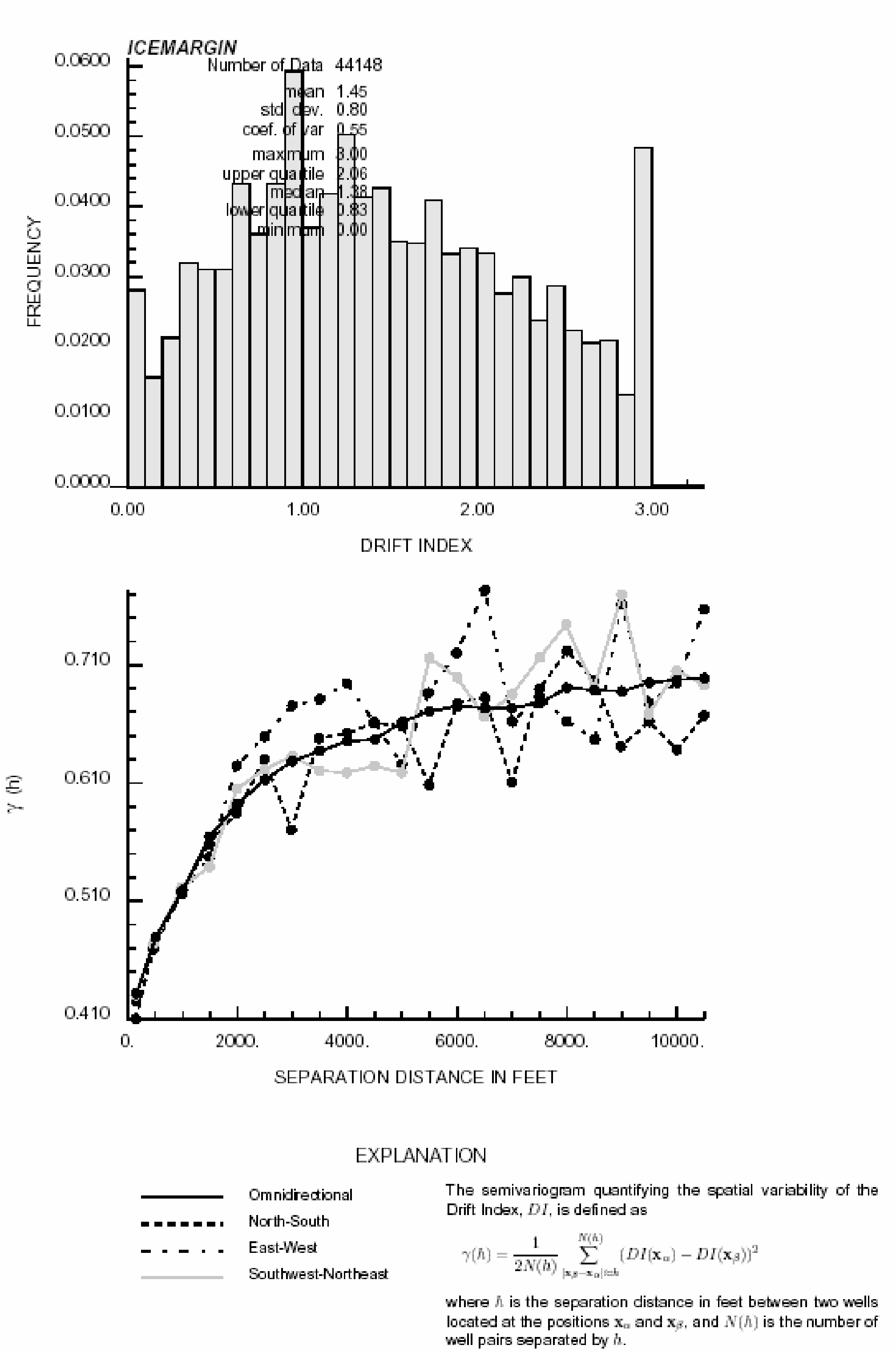


Figure 4.2.6. Histogram and semivariograms of Drift Index values for the Ice-Marginal Till Landsystem.

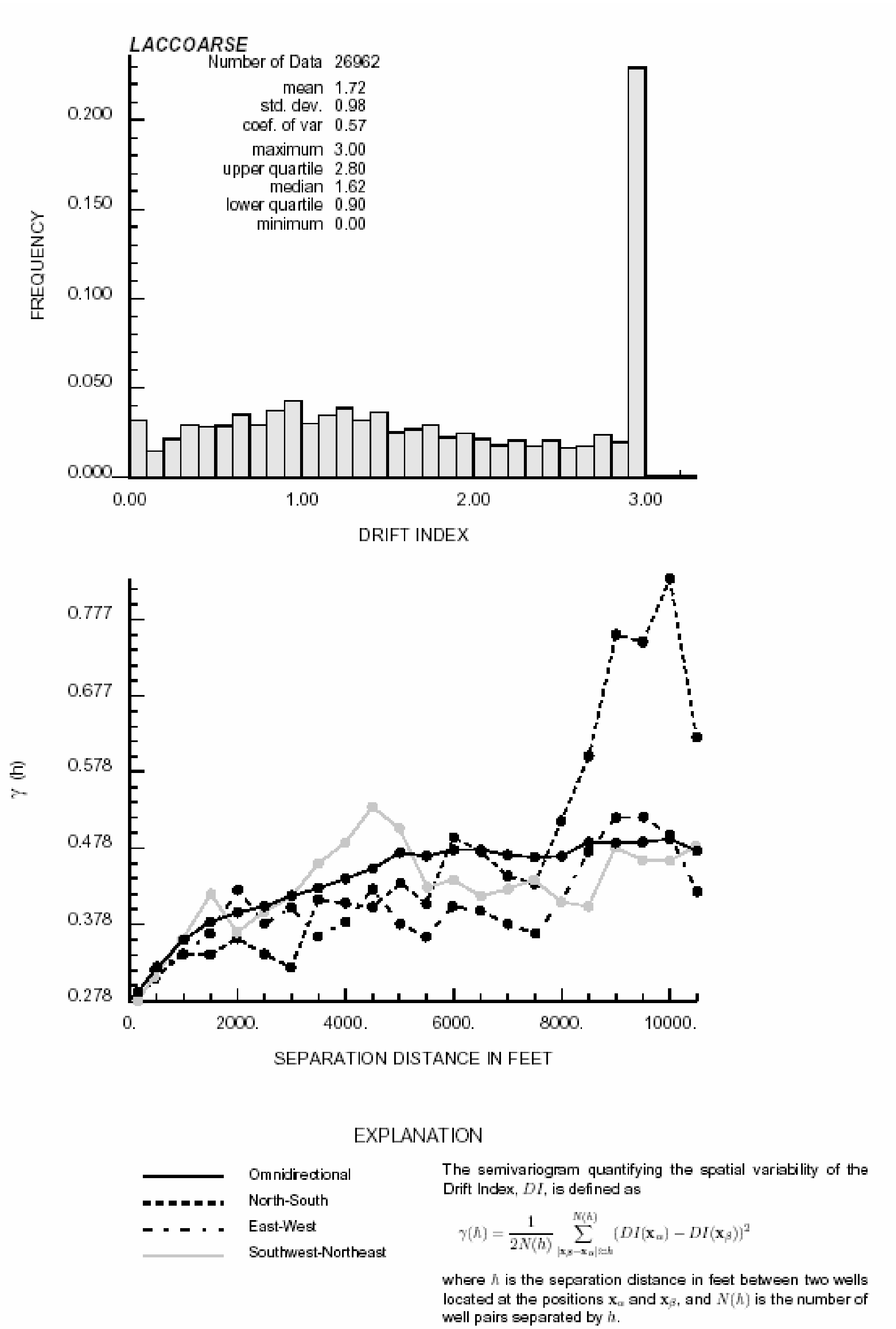


Figure 4.2.7. Histogram and semivariograms of Drift Index values for the Lacustrine Coarse Landsystem.

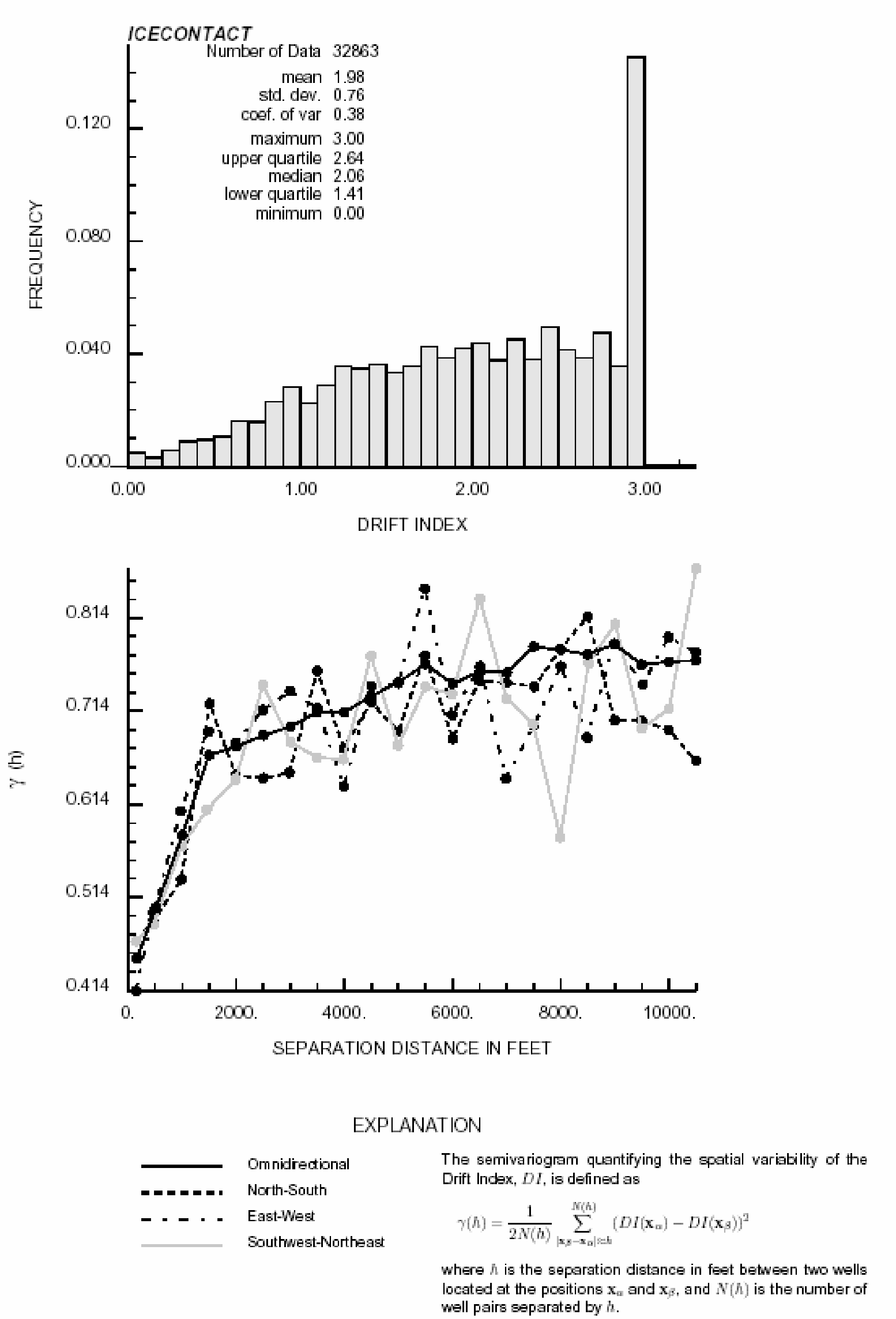


Figure 4.2.8. Histogram and semivariograms of Drift Index values for the Ice-Contact Outwash Landsystem.

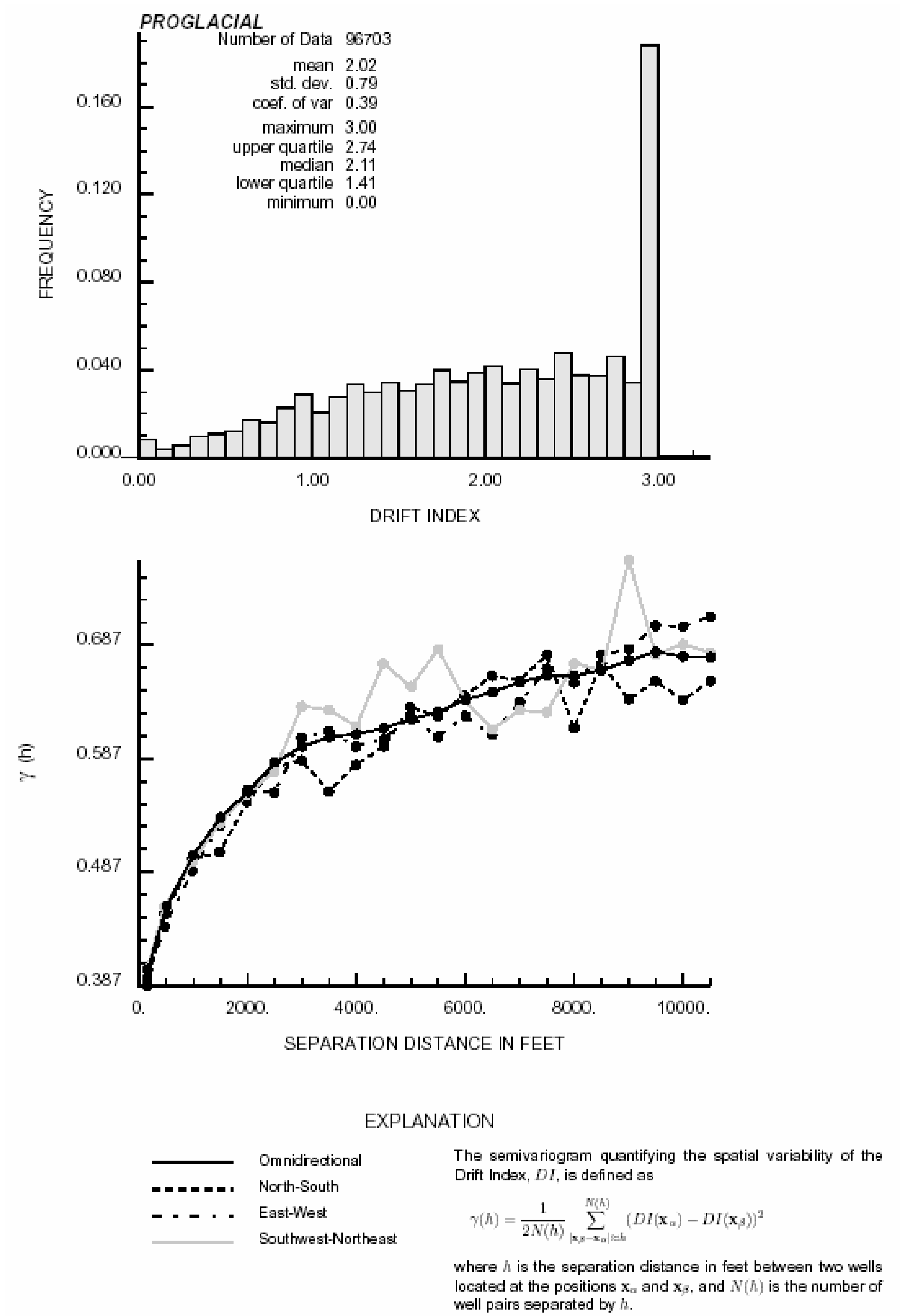


Figure 4.2.9. Histogram and semivariograms of Drift Index values for the Proglacial Outwash Landsystem.

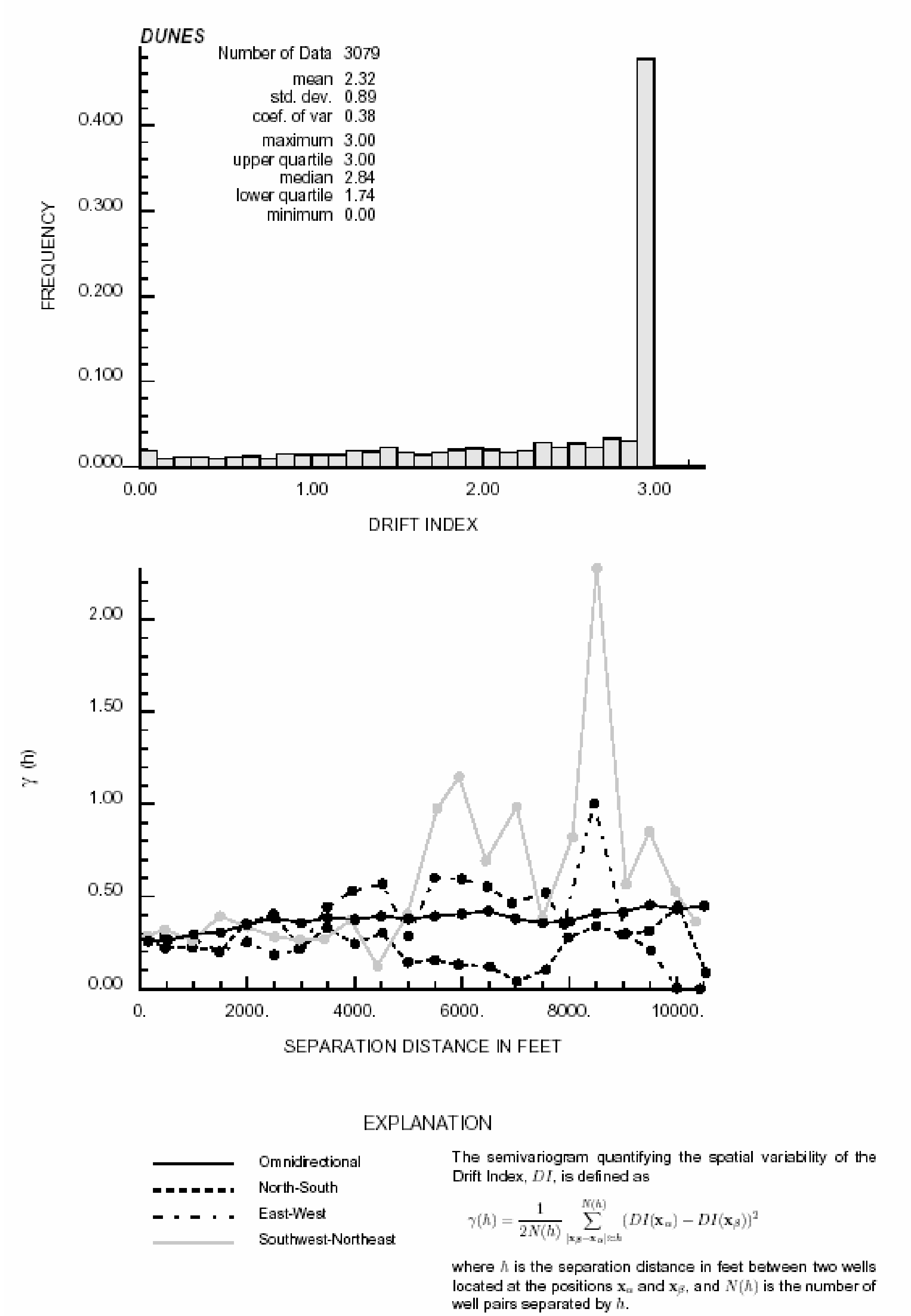


Figure 4.2.10. Histogram and semivariograms of Drift Index values for the Coastal Dunes Landsystem.

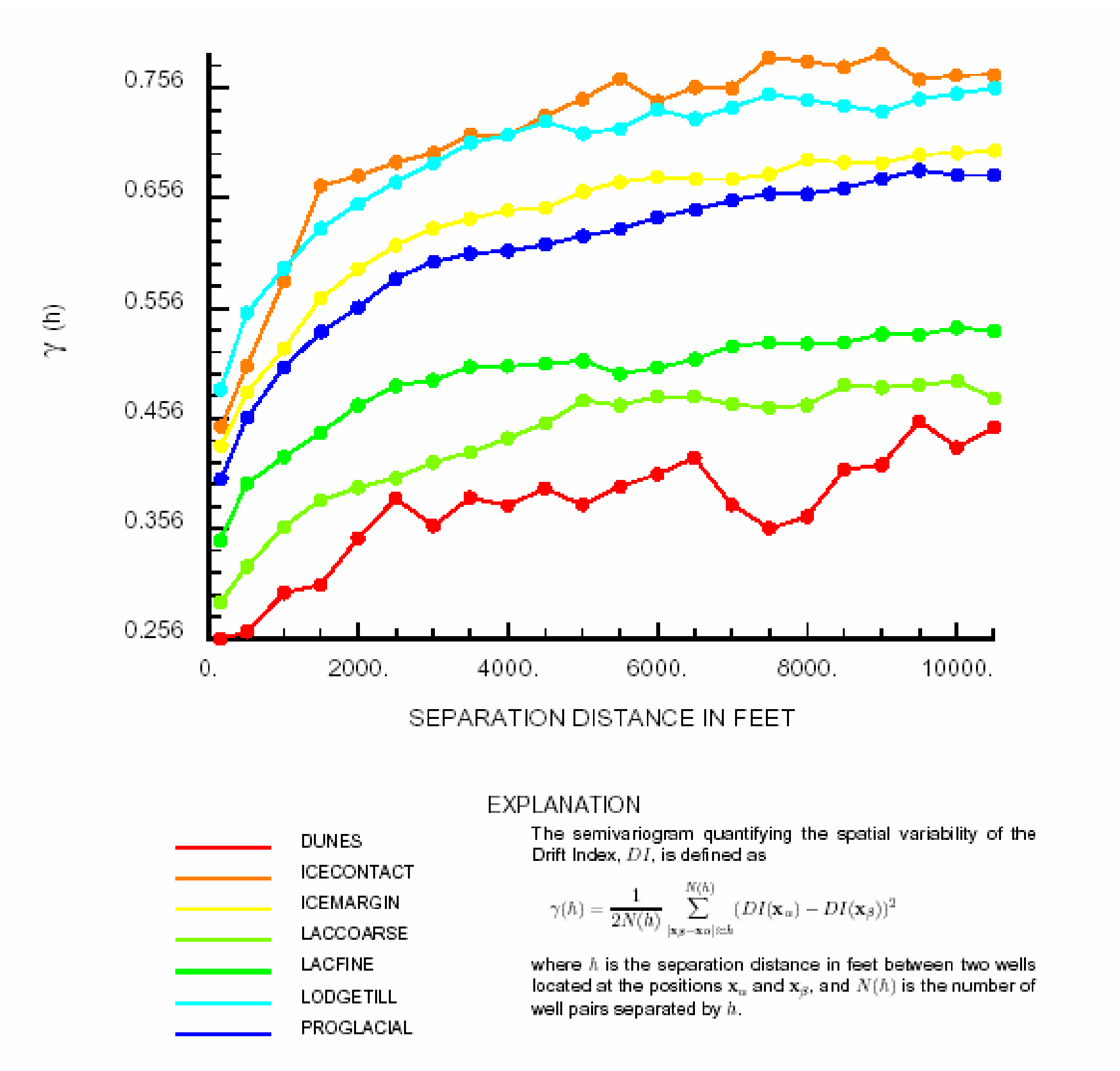


Figure 4.2.11. Summary of semivariograms for Drift Index of the seven glacial landystems for Michigan.

4.2.1.3 Depth of the Various Landsystems

An argument against the use of the landsystem map for estimating aquifer yields is that there are areas of the state where the major glacial aquifers do not correspond to the interpreted landsystem on the surface. Although the anticipated pattern of median DI by landsystem has been shown (Figure 4.2.3), the interpretive value of the landsystem framework has been called into question by some. In this section, the spatial distribution of Drift Index values is examined between selected landsystems to demonstrate their interpretive value.

A previous section (4.2.1.2) presented the method used to calculate the Drift Index both for the total depth of a drift well, or the drift portion of a rock well, as well as within the established depth increments (0 – 20 ft; 21 – 40 ft; 41 – 60 ft; 61 – 80 ft; 81 – 100 ft; 101 – 125 ft; 126 – 150 ft; 151 – 200 ft; ... 401 – 450 ft). In this section, the relationship between Drift Index variability with depth and the glacial landsystems map will be explored. Figure 4.2.12 shows the overall Drift Index, Figure 4.2.13 shows the Drift Index for the 0-20 ft. depth range and Figure 4.2.14 shows the Drift Index for the 21-40 ft. depth increment.

In several areas of the state (e.g., SE Michigan, particularly in the Monroe – Lenawee county area), aquifer material dominates the near-surface portion of the glacial sediments, but overlies finer-texture glacial units at a depth of 21 – 40 feet. These changes in drift texture with depth can be more easily seen by differencing the various maps in GIS.

Figure 4.2.15 highlights the differences between the overall Drift Index and the Drift Index for the 0 – 20 ft. depth increment. The differences between the overall Drift Index and the Drift Index for the 21 – 40 ft. depth range are shown in Figure 4.2.16. The contrast in drift texture between the upper 20 feet of the drift and the next 20 ft.increment is shown in Figure 4.2.17.

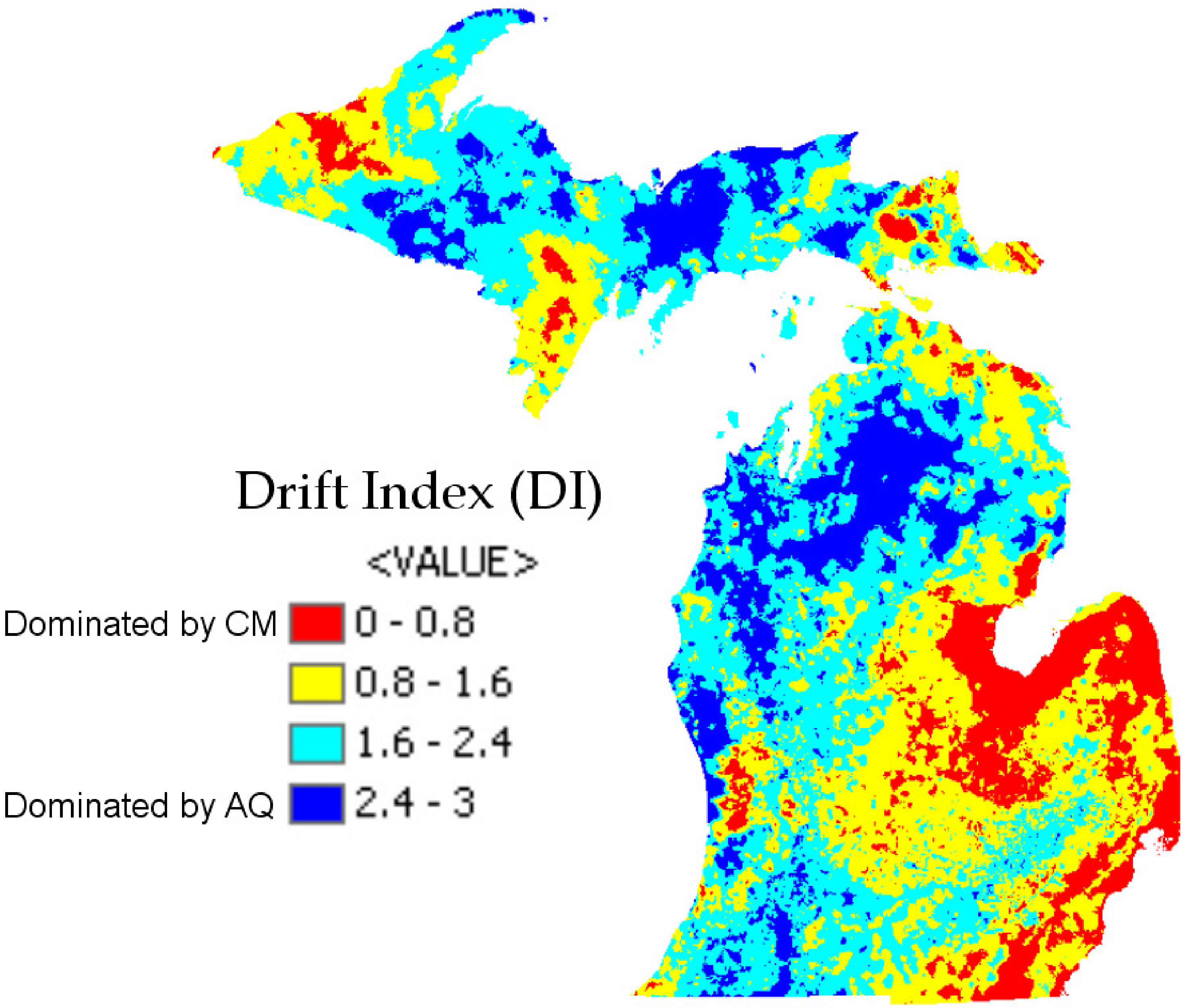


Figure 4.2.12. Overall Drift Index for the total depth of a drift well or the drift portion of a rock well.

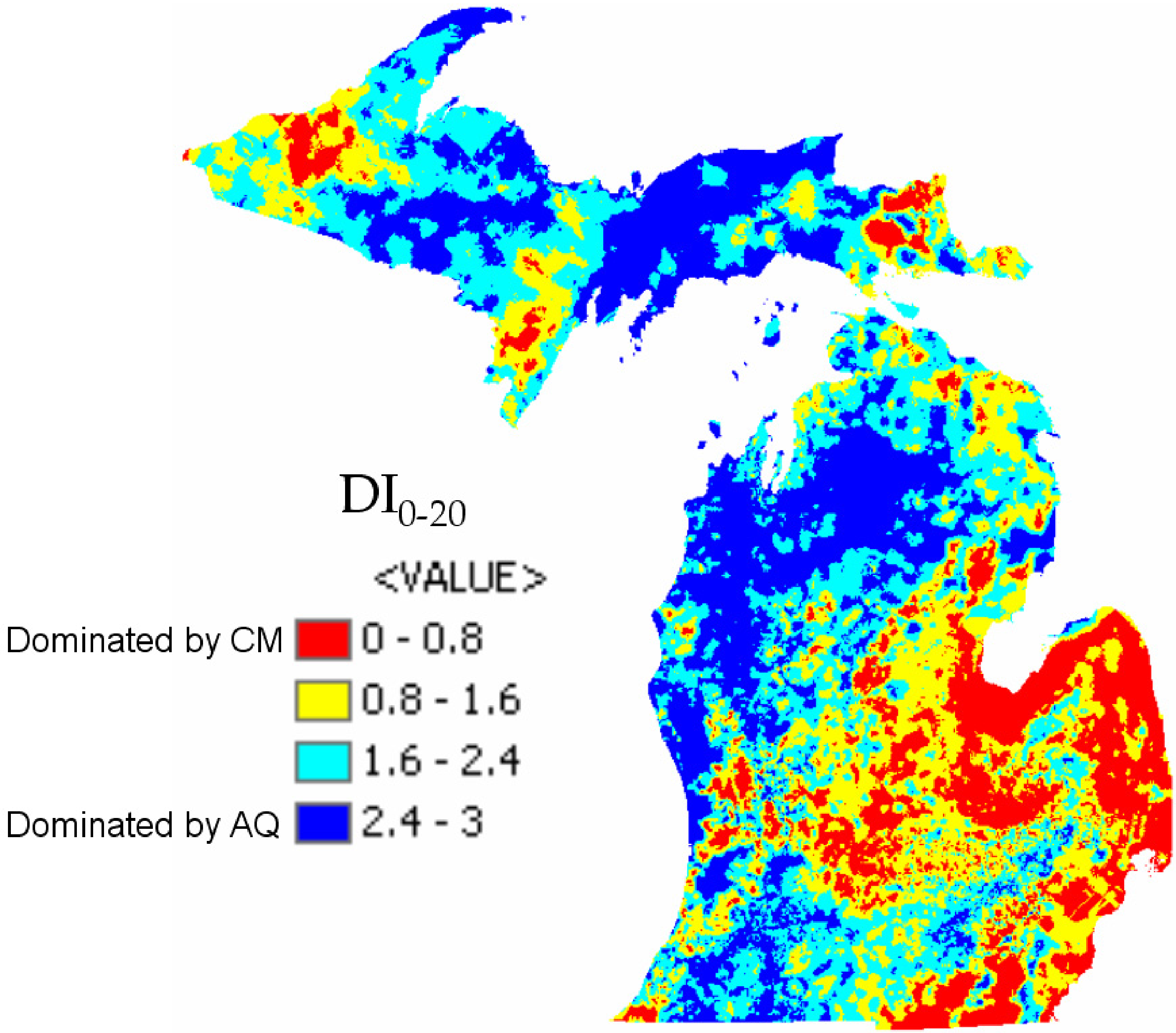


Figure 4.2.13. Drift Index values for depths 0 – 20 feet.

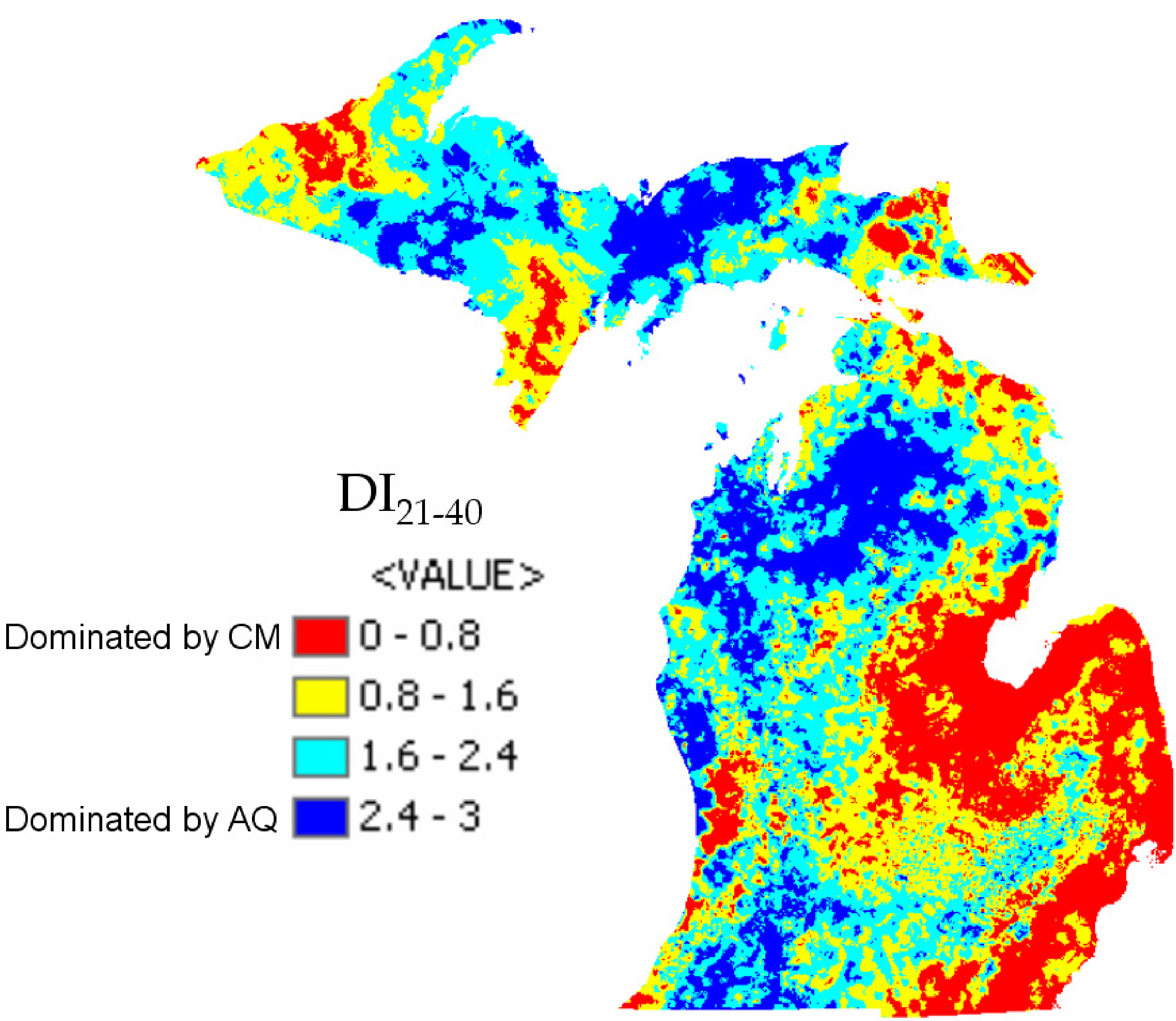


Figure 4.2.14. Drift Index values for depths 21 – 40 feet.

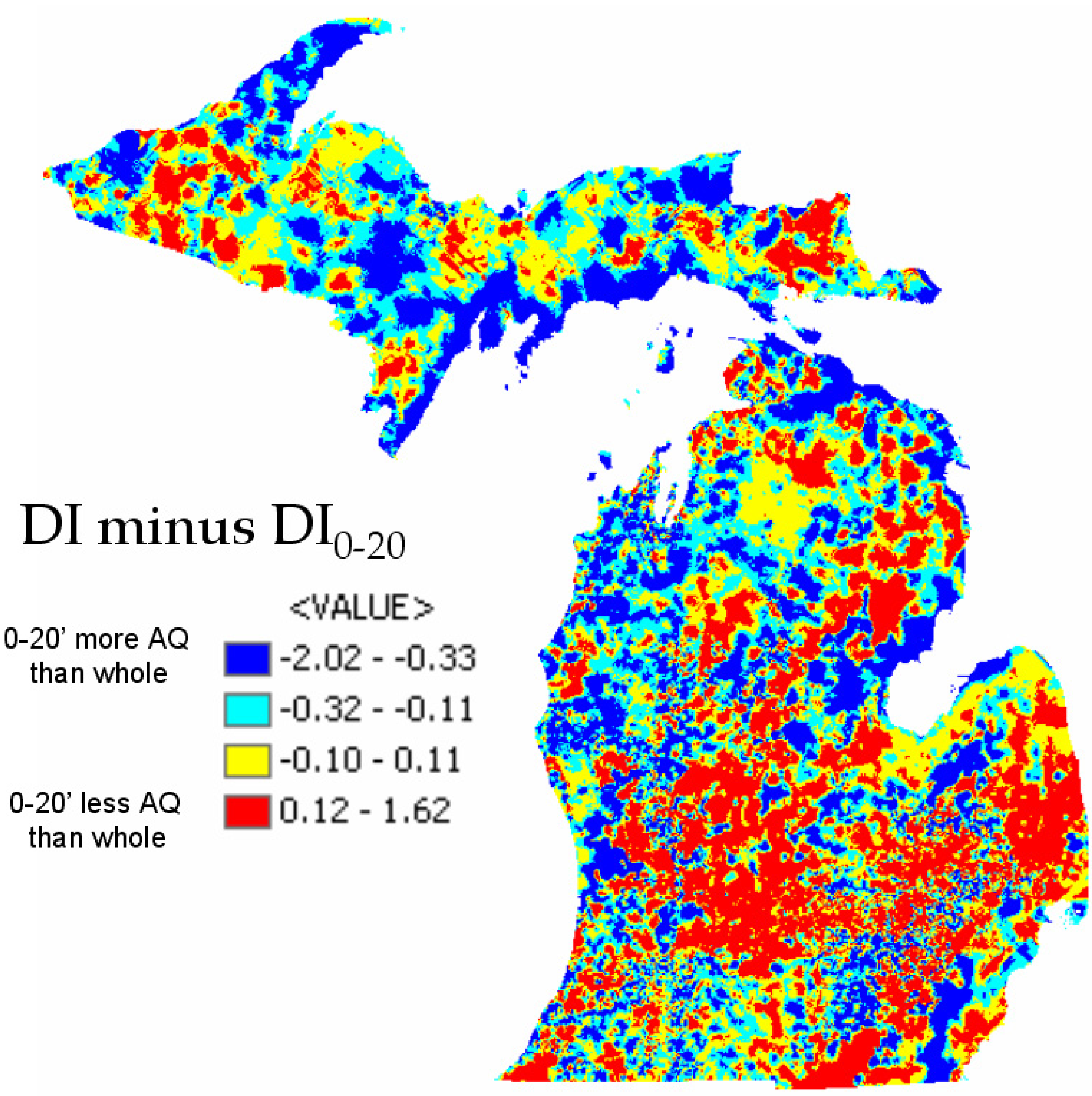


Figure 4.2.15. Difference between the overall Drift Index and the Drift Index for 0 – 20 ft.

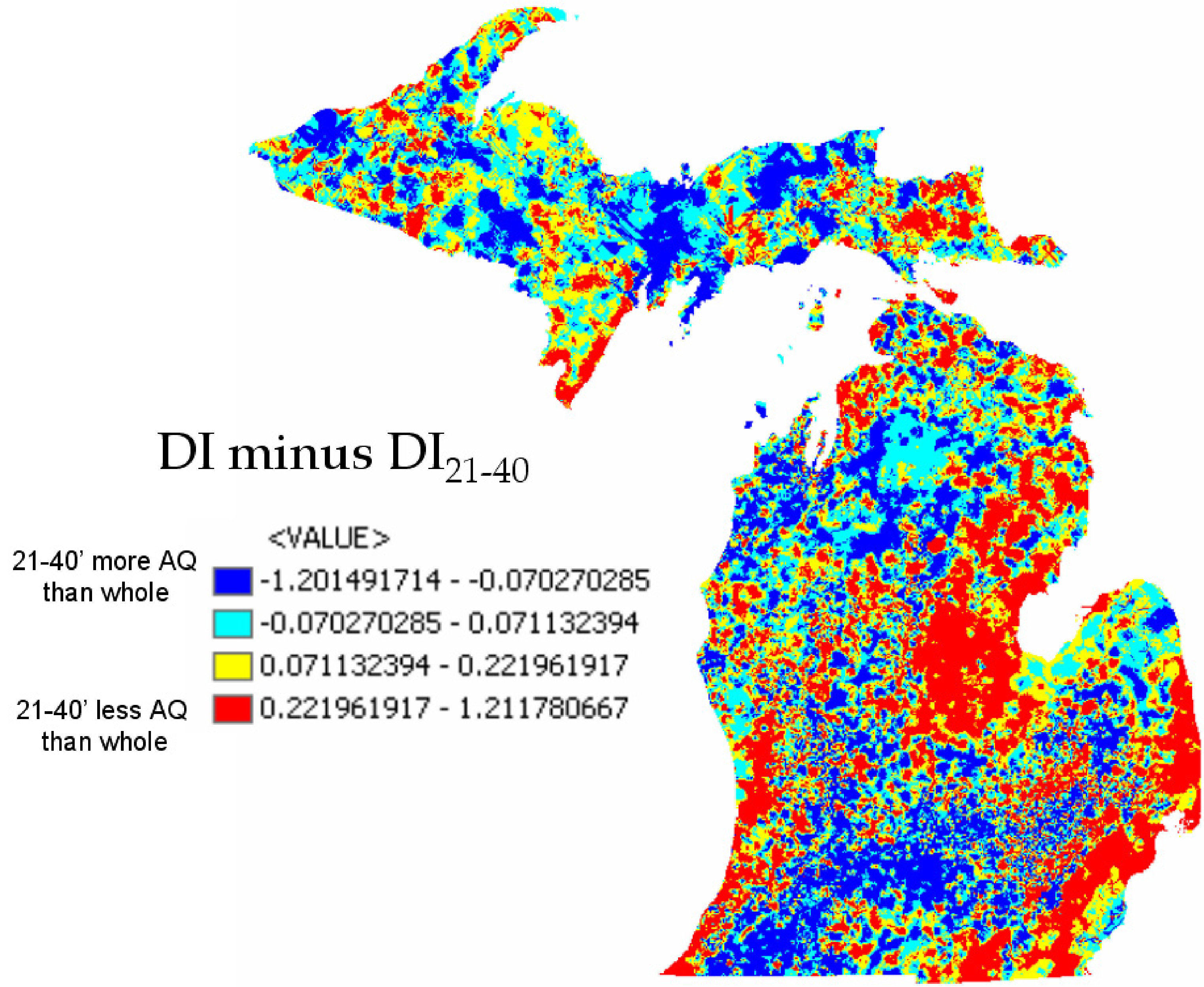


Figure 4.2.16. Difference between the overall Drift Index and the Drift Index for 21 – 40 ft.

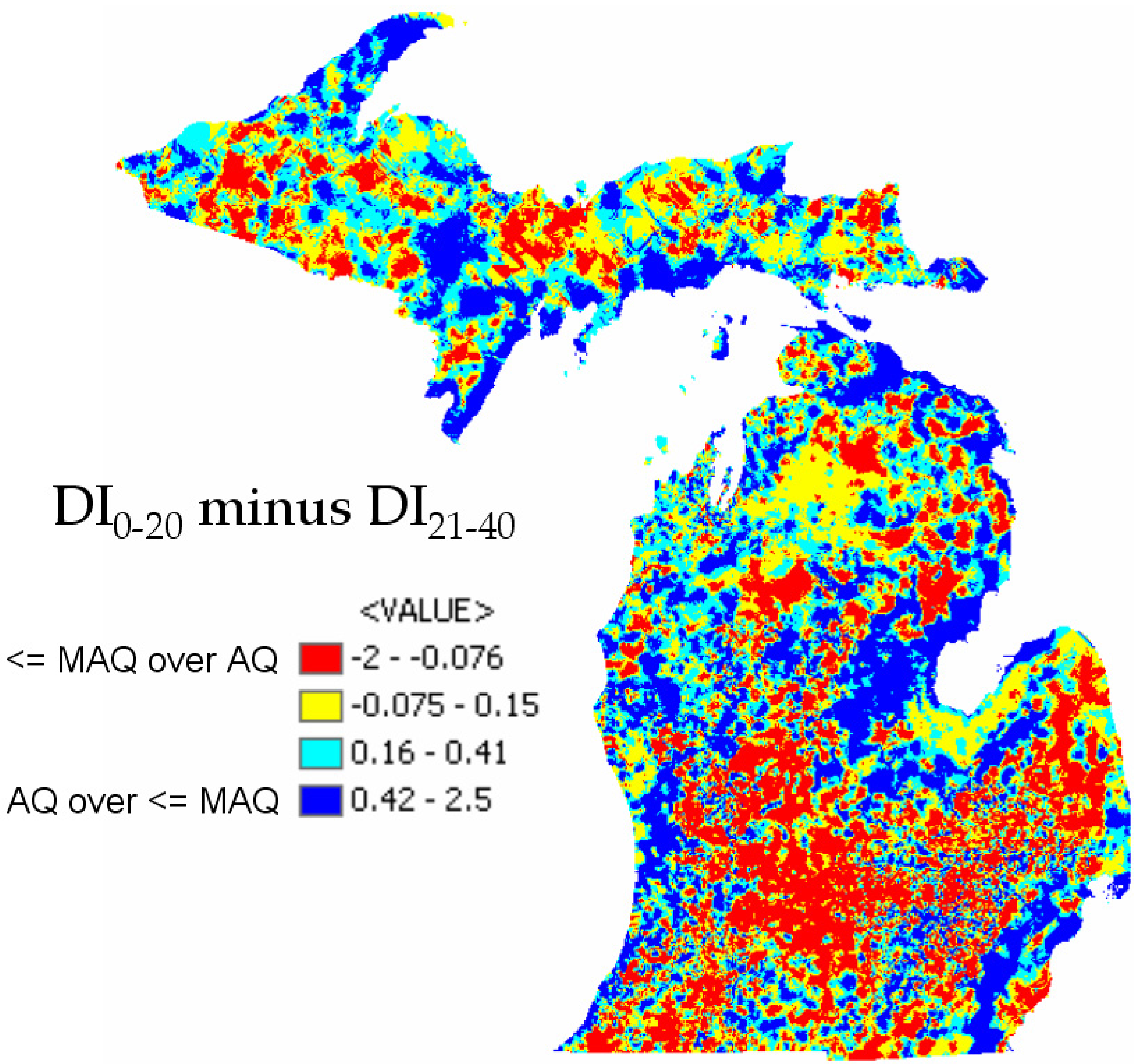


Figure 4.2.17. Drift Index difference between the 0 – 20 ft. and 21 – 40 ft. increments.

When Frank Leverett first studied the outwash of Oakland County (Leverett, 1900), he used the term "great gravel plain" to describe the interlobate outwash plain that trends NE-SW across the county. In places, the surface of this outwash deposit exhibits considerable local relief due to the presence of kames, older morainic fragments partially buried in the outwash and the numerous kettles in the form of dry depressions, marshes and lakes. So much glaciofluvial sediment was deposited in contact with stagnant ice blocks in Oakland County that no other large area in the Southern Peninsula has more lakes (Rieck, Winters and Lusch, 1985). Figure 4.2.18 depicts Leverett's "great gravel plain" across Oakland, southeastern Livingston, western Washtenaw and eastern Jackson counties (stippled areas = the proglacial outwash and ice-contact outwash landsystems) on top of the Drift Index map for the upper 40 feet of the drift. The spatial correspondence between these two maps is striking, especially considering the nature of the Kringing interpolation that was used to create the Drift Index map from the *Wellogic* point file. Most of these two landsystems are dominated by coarse-texture, aquifer materials (sand and gravel) to at least a depth of 40 feet. The Defiance spillway, which carried outwash discharges southwestward along the ice front when it was forming the Defiance Moraine, also shows up as a narrow, but thicker, accumulation of coarse-texture drift, especially in the vicinity of Tecumseh.

Southwest Lower Michigan, especially the part glaciated by the Michigan Ice Lobe, has long been noted as an area dominated by coarse-texture drift. Figure 4.2.19 shows that these surface deposits extend to a depth of at least 40 feet across much of the region. At the northern end of this outwash complex, the Gun River outwash plain serves as a good example of a moderately thick outwash system in which the upper 20 feet are dominated by aquifer-type materials, while the 21 – 40 ft. zone is dominated by marginal aquifer or or partially confining materials (compare Figures 4.2.20a and b).

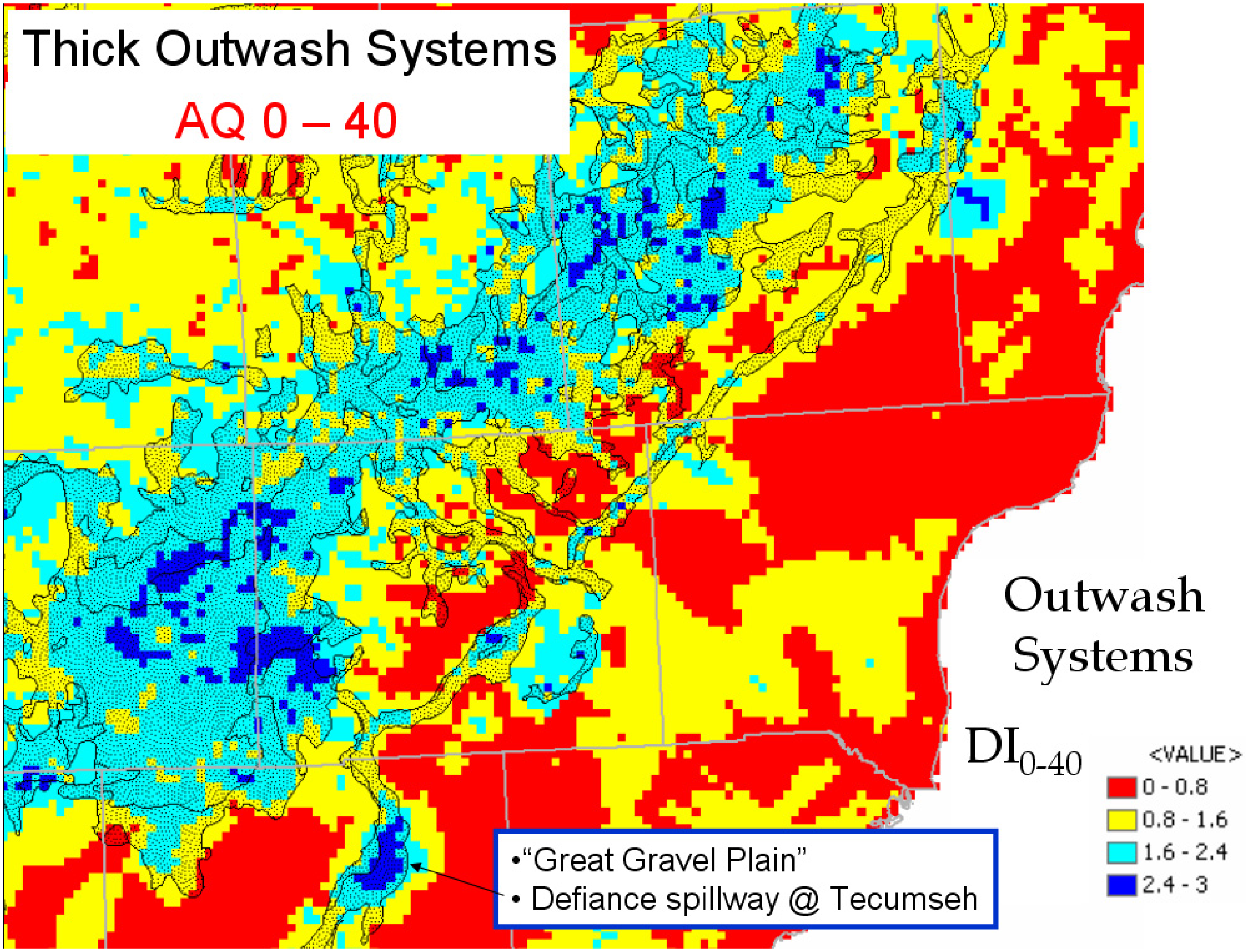


Figure 4.2.18. Example of the thick (at least 40 feet of material) outwash systems in southeast Lower Michigan as shown on the Drift Index map.

Other examples of moderately thick outwash systems include the Grand River valley from Lowell to Grandville across Ionia and Kent counties (Figure 4.2.21a and b) and the Grass Lake collapsed outwash plain in southeastern Jackson County (Figure 4.2.22a and b). In contrast, some outwash deposits are relatively thin. The Looking Glass, Shiawassee and Swartz Creek spillways in central Lower Michigan are good examples of this type of deposit as indicated by the similarity between the $DI_{0\text{-}20}$ and $DI_{21\text{-}40}$ (Figure 4.2.23a and b).

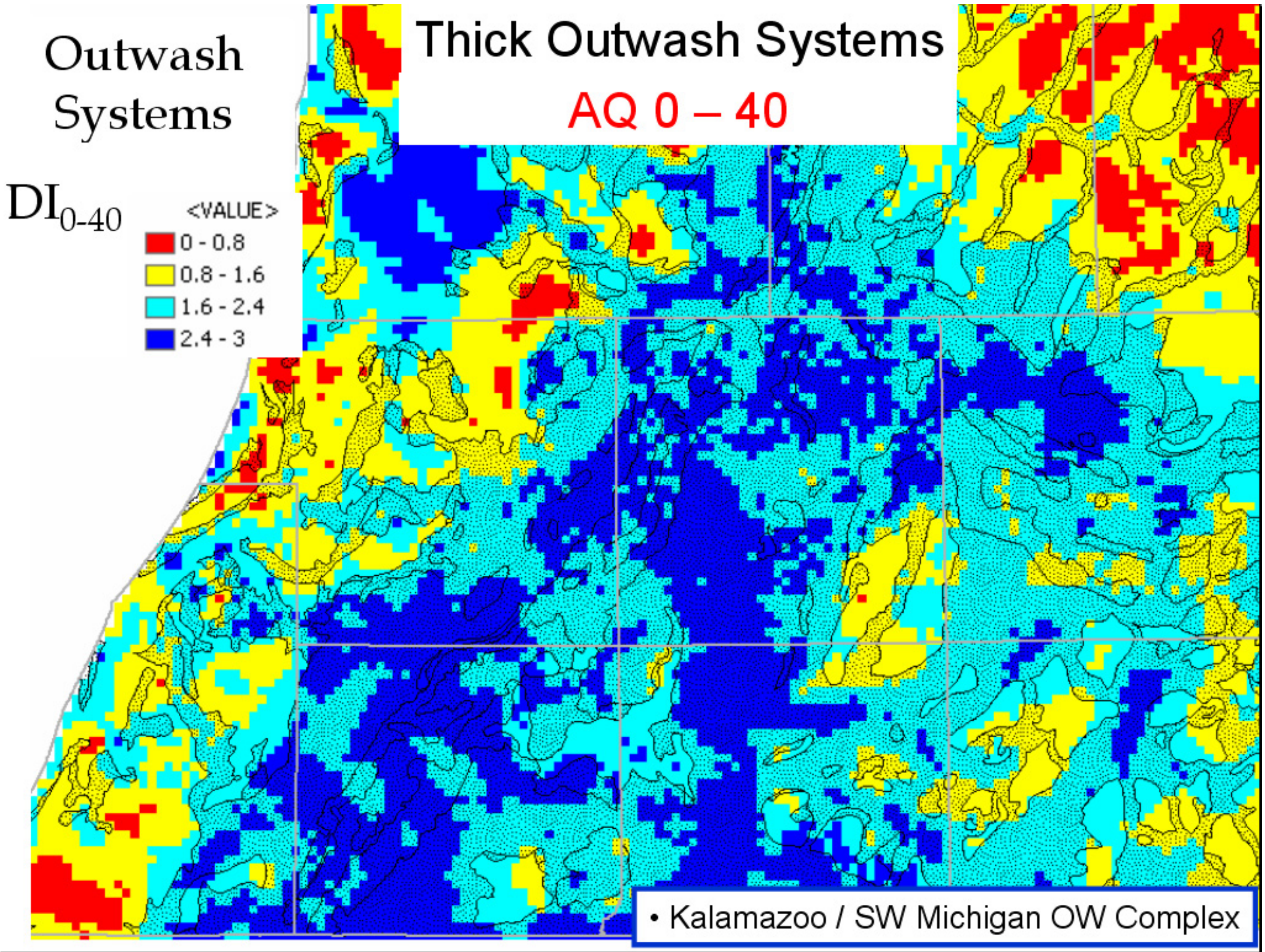


Figure 4.2.19. Example of the thick (at least 40 feet of material) outwash systems in southwest Lower Michigan as shown on the Drift Index map.

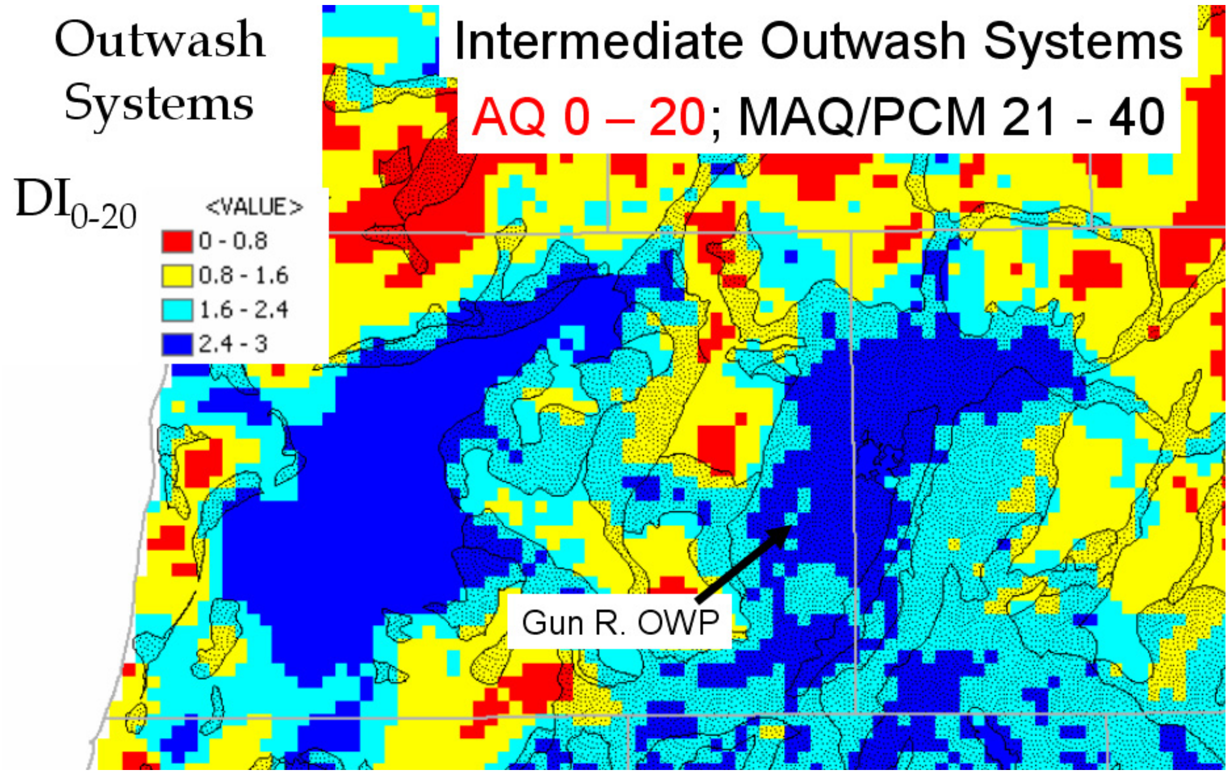


Figure 4.2.20a. Moderately thick Gun River outwash plain: 0-20 ft. depth.

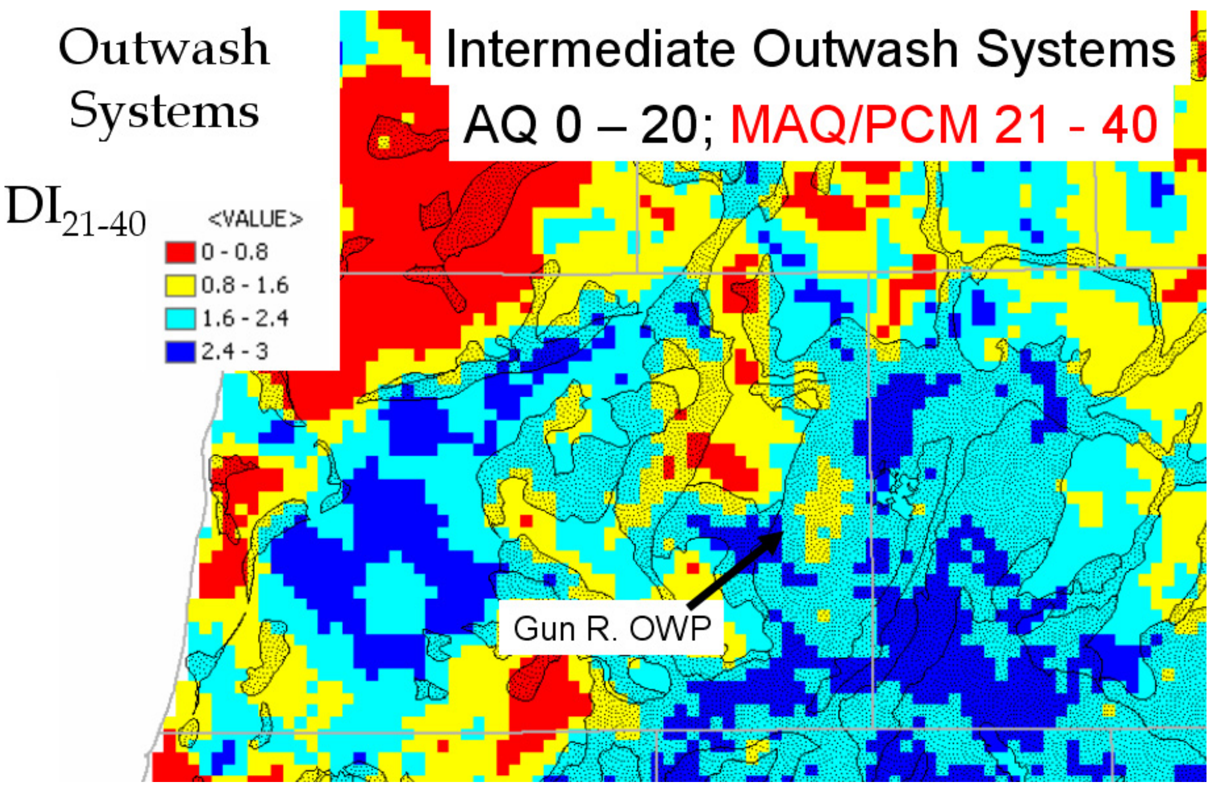


Figure 4.2.20b. Moderately thick Gun River outwash plain: 21-40 ft. depth.

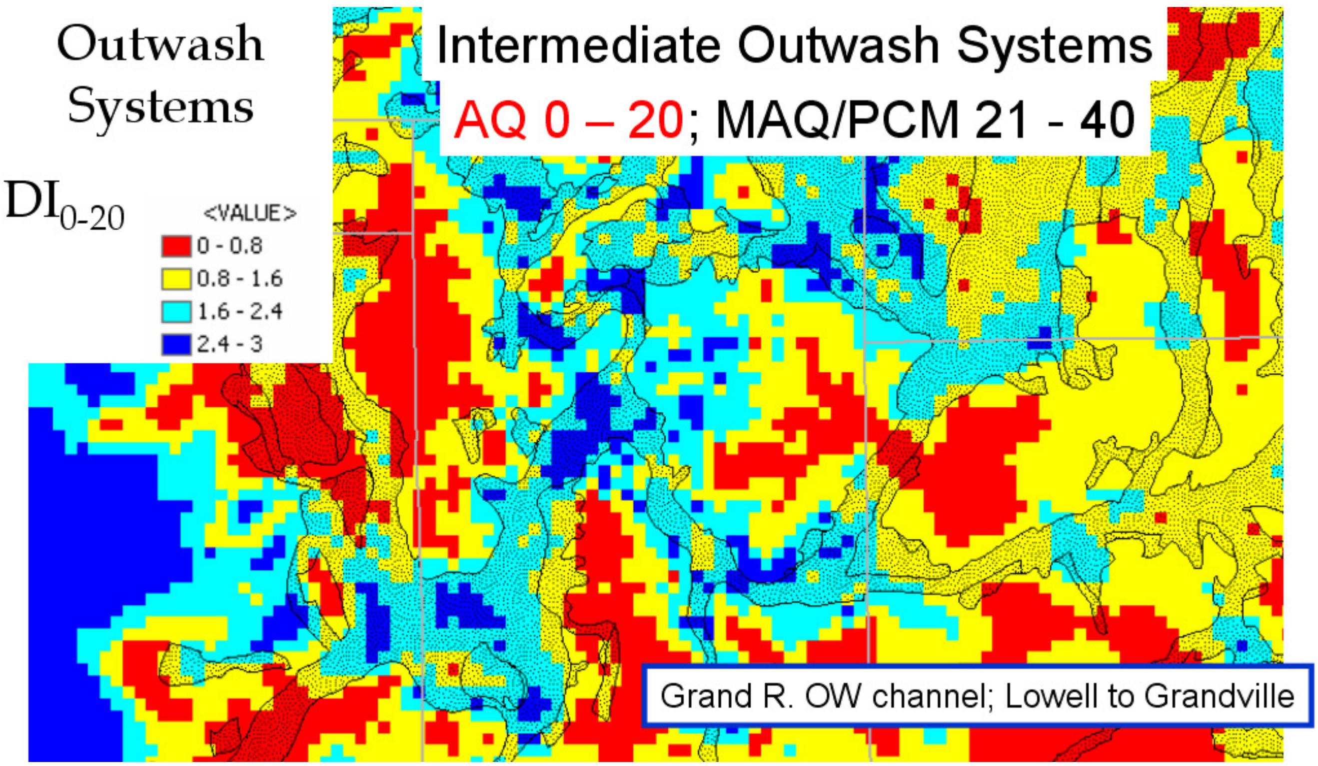


Figure 4.2.21a. Moderately thick lower Grand River outwash plain: 0-20 ft. depth.

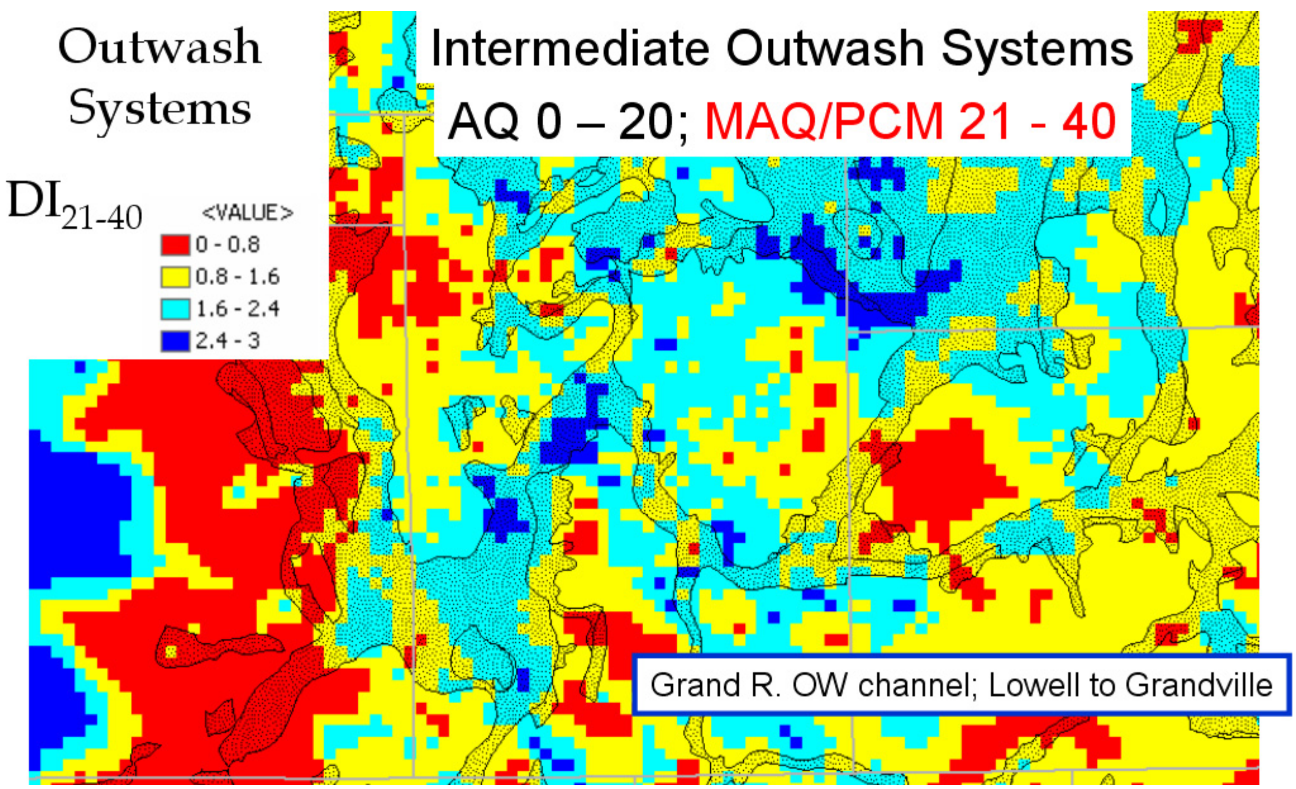


Figure 4.2.21b. Moderately thick lower Grand River outwash plain: 21-40 ft. depth.

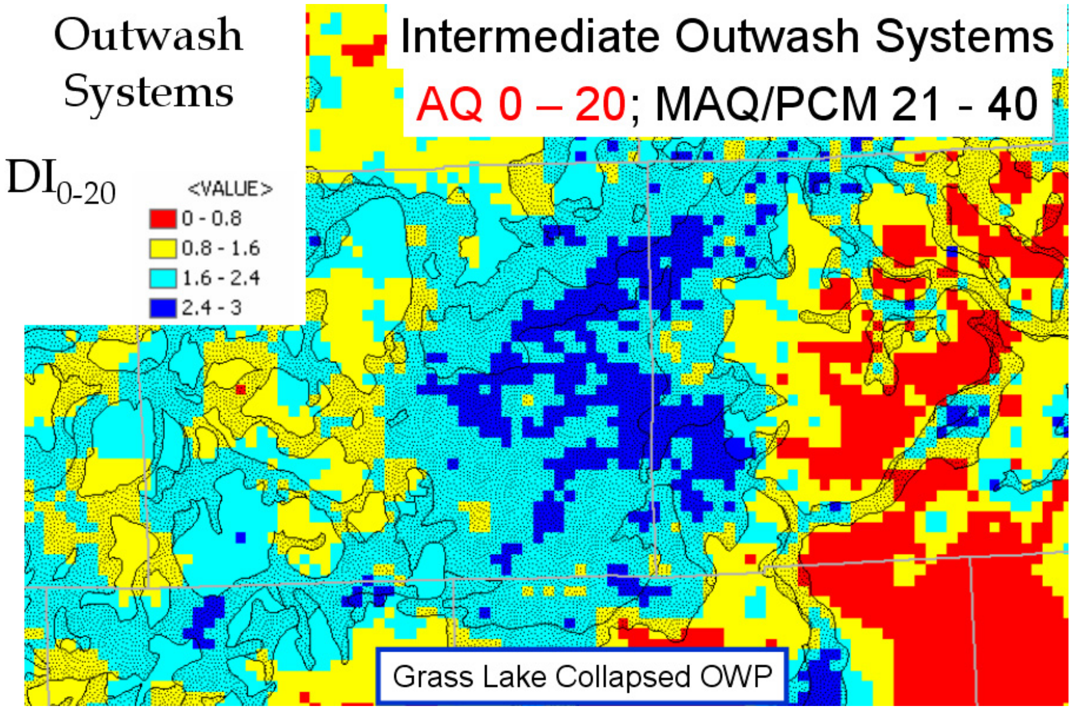


Figure 4.2.22a. Moderately thick Grass Lake collapsed outwash plain: 0-20 ft. depth.

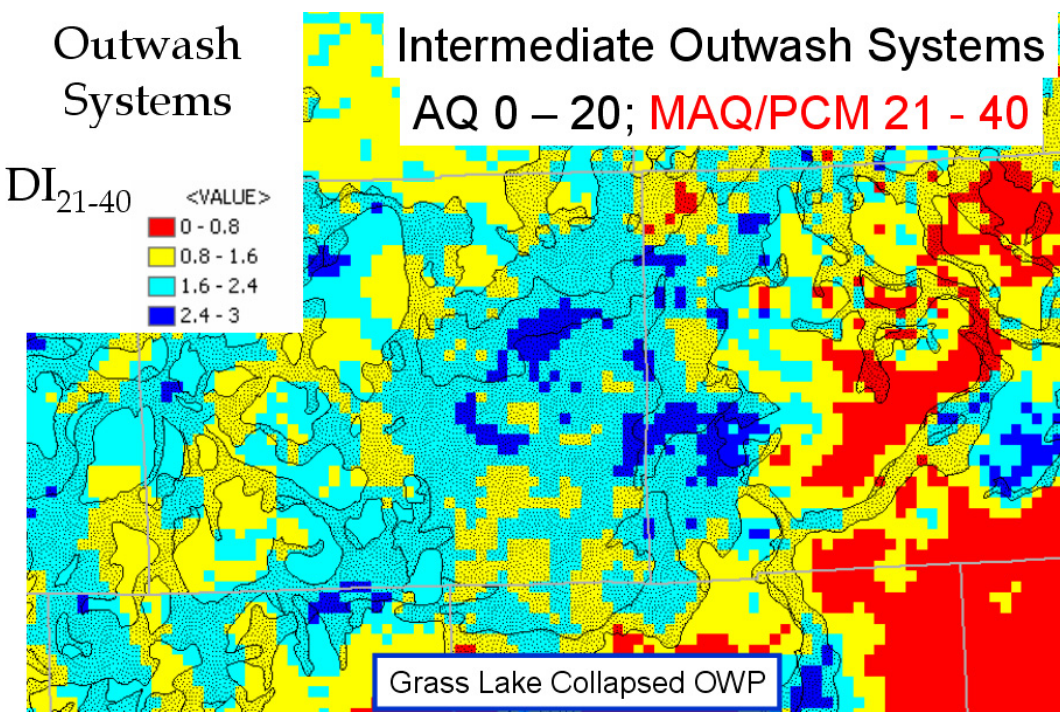


Figure 4.2.22b. Moderately thick Grass Lake collapsed outwash plain: 21-40 ft. depth.

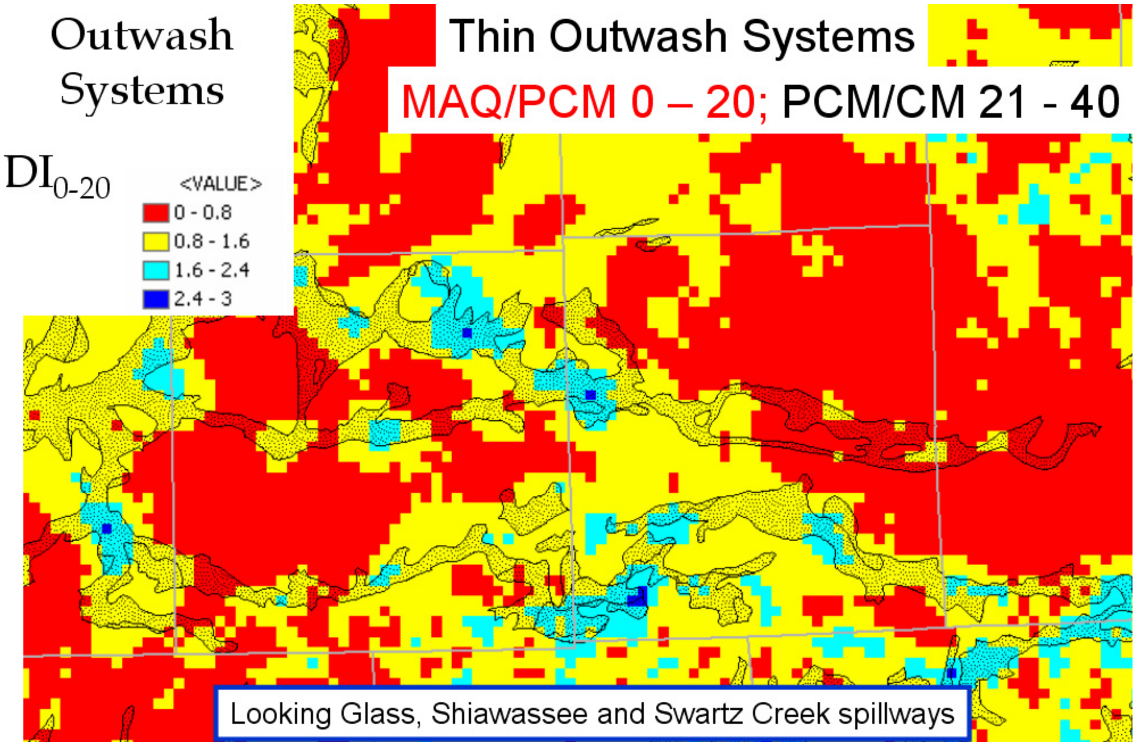


Figure 4.2.23a. Thin outwash plains (spillways) in mid-Michigan: 0-20 ft. depth.

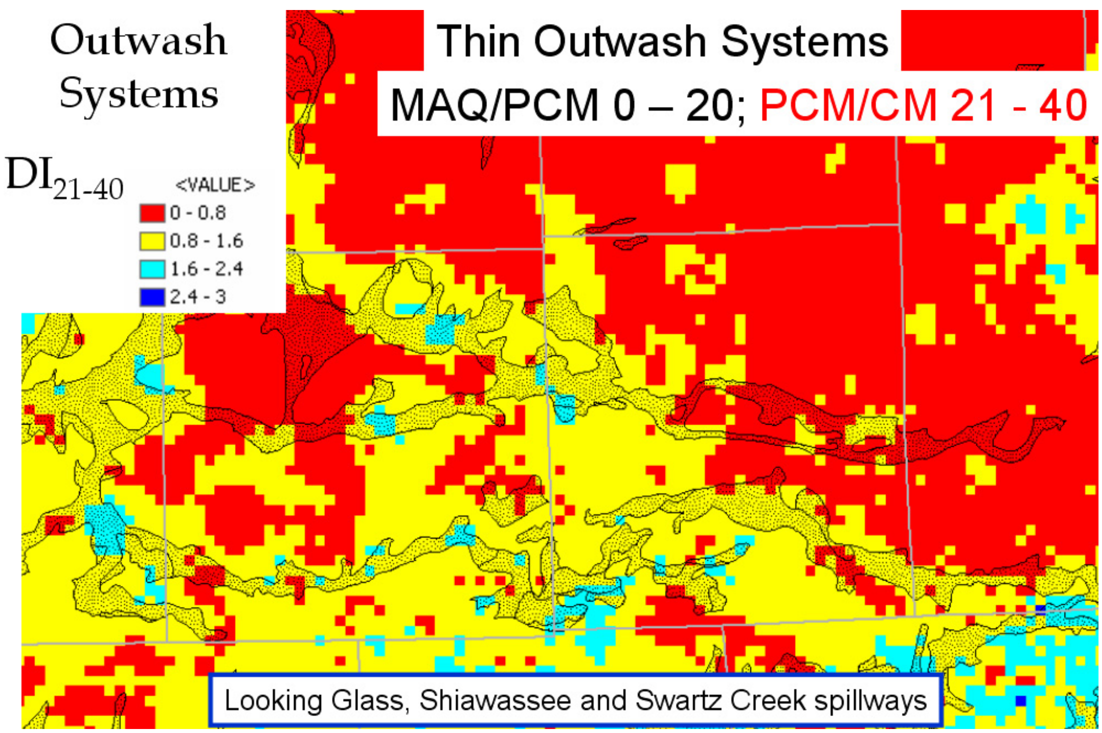


Figure 4.2.23b. Thin outwash plains (spillways) in mid-Michigan: 21-40 ft. depth.

The close spatial relationship between the landsystems map and the variability of Drift Index values with depth is very nicely shown when considering the various deltas that formed along the shores of the Glacial Great Lakes. These deltaic systems are components of the lacustrine coarse landsystem, which is shown by the cross-hatch pattern on Figures 4.2.24 – 4.2.30. Other members of the lacustrine coarse landsystem include beach ridges, offshore bar deposits and the eolian sand deposits derived from them both. Figure 4.2.24 depicts the thick (at least 40 feet) glacial delta of the Au Sable River in Iosco County. Both the upper and lower deltas, each graded to different proglacial lakes, can be seen. The Kalamazoo River delta in Allegan County, shown in Figure 4.2.25, is another fine example of a thick delta deposit.

The Cedar River delta at Gladwin in Clare County (Figure 4.2.26) and the Cass River delta/embayment deposit in Tuscola County (Figure 4.2.27) are good examples of moderately thick lacustrine landsystems. In these systems, the upper 20 feet of the drift is a mixture of aquifer and partially confining materials, while the next 20 feet (21-40 ft.) is a mixture of partially confining and confining materials. The Chippewa River delta east of Mt. Pleasant in Isabella County (Figure 4.2.28), the Huron River delta downstream from Ypsilanti in Washtenaw County (Figure 4.2.29) and the Grand River delta at Allendale in Ottawa County (Figure 4.2.30) are examples of thin delta deposits in which the upper 20 feet of the drift is a mixture of aquifer and partially confining materials, but the next 20 feet (21-40 ft.) is dominated by confining materials.

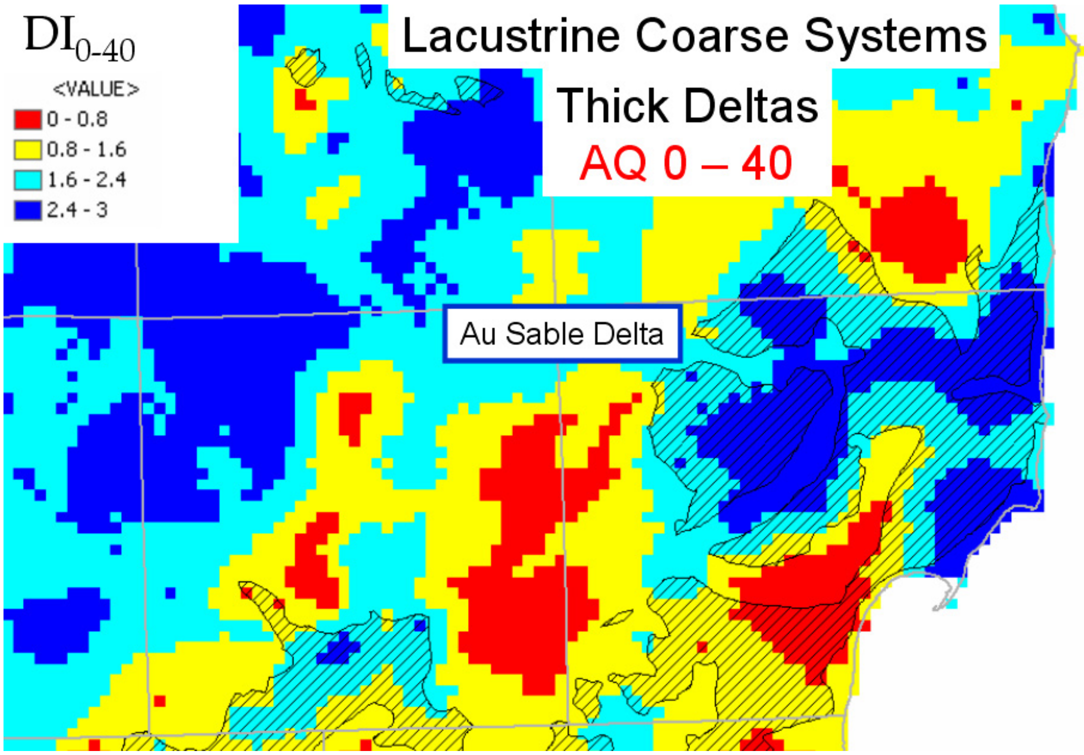


Figure 4.2.24. Glacial Au Sable River delta.

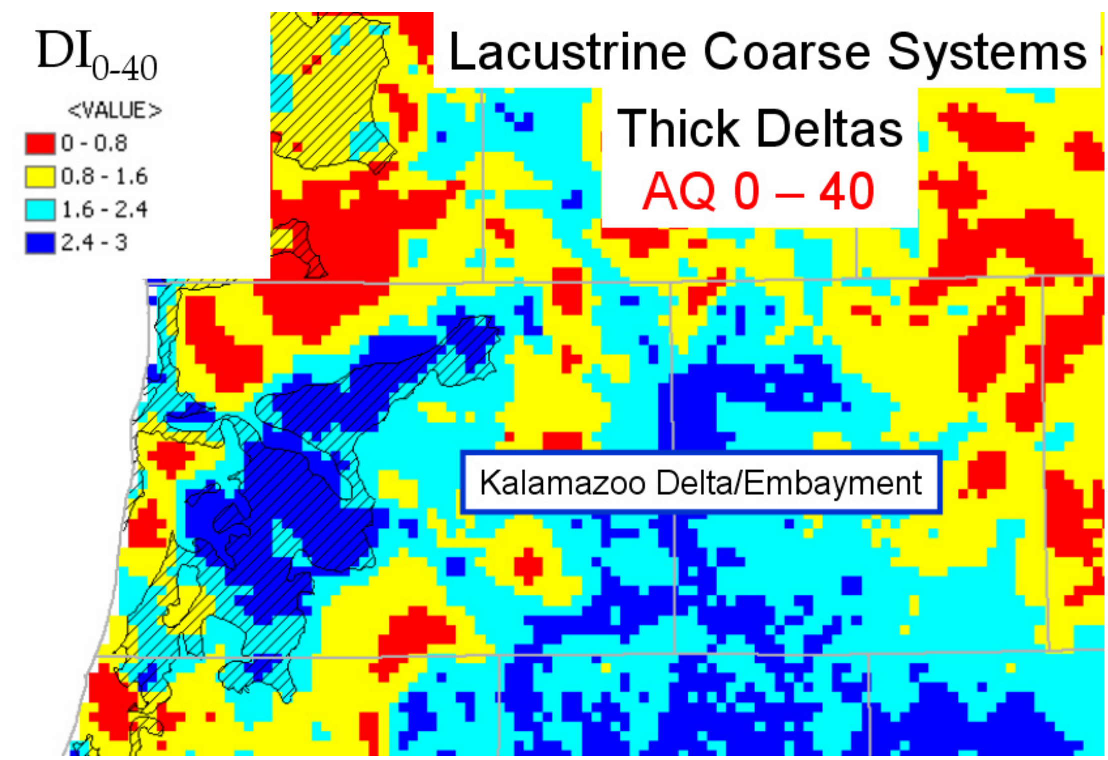


Figure 4.2.25. Glacial Kalamazoo River deltaic deposits
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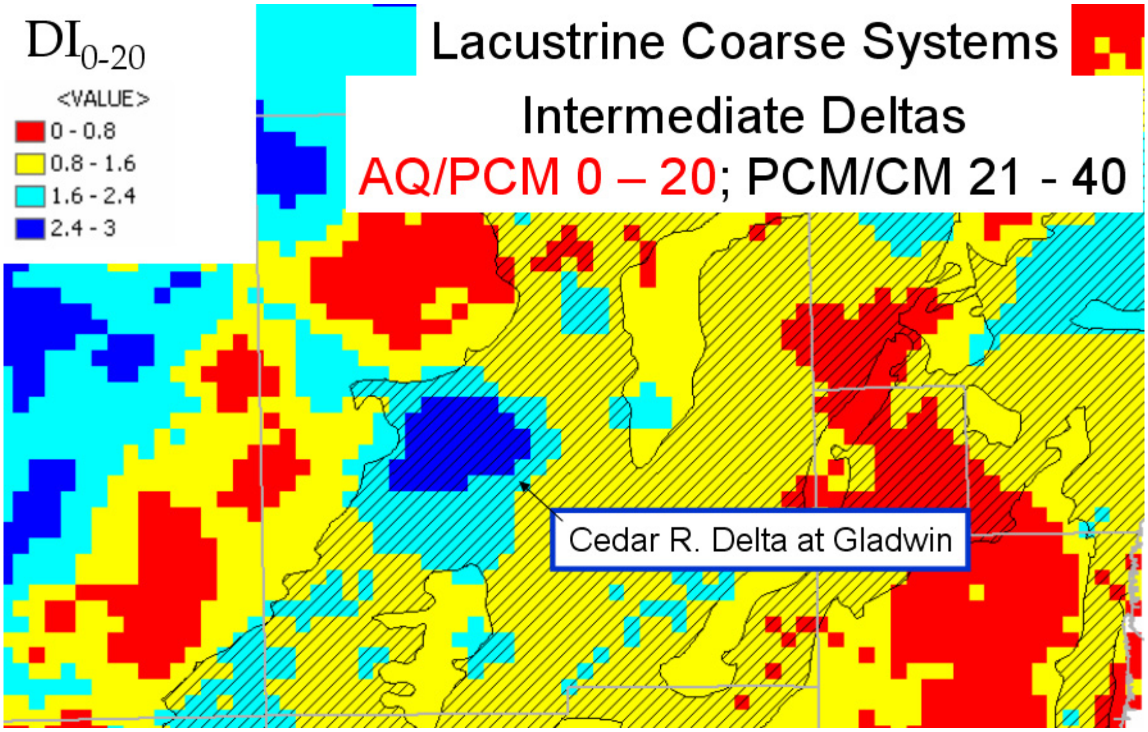

Figure 4.2.26a. Glacial Cedar River delta – 0 to 20 ft. depth range
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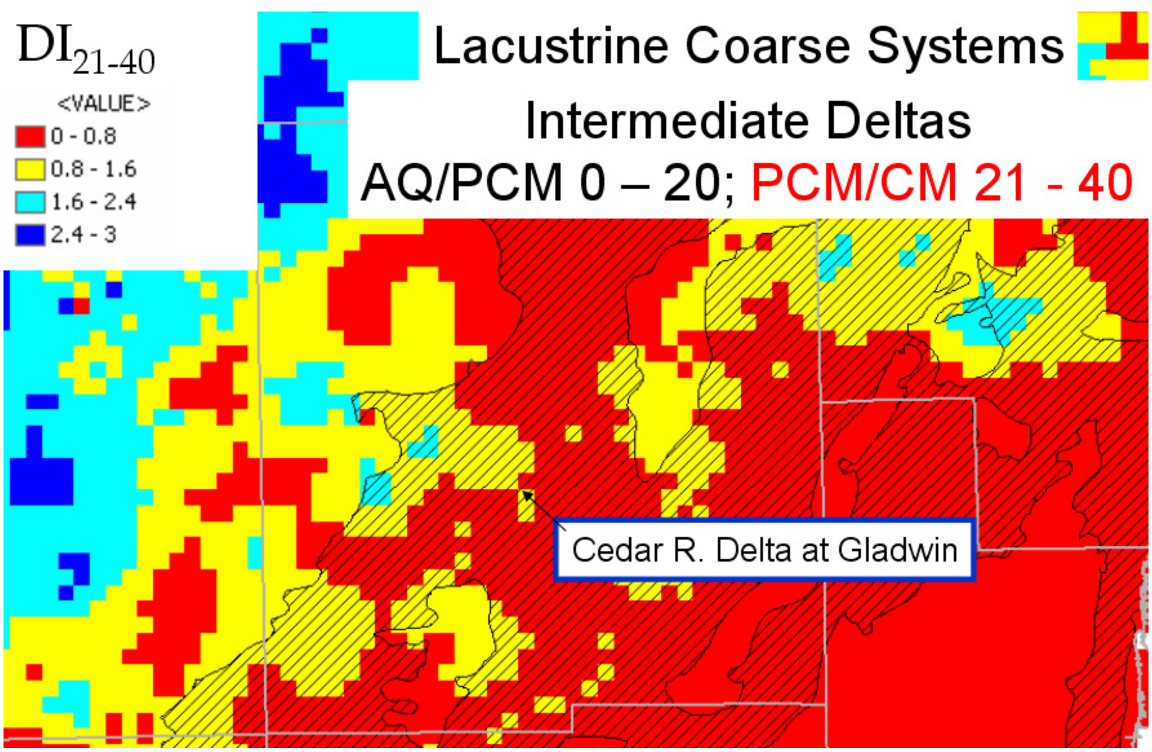

Figure 4.2.26b. Glacial Cedar River delta – 21 to 40 ft. depth range.

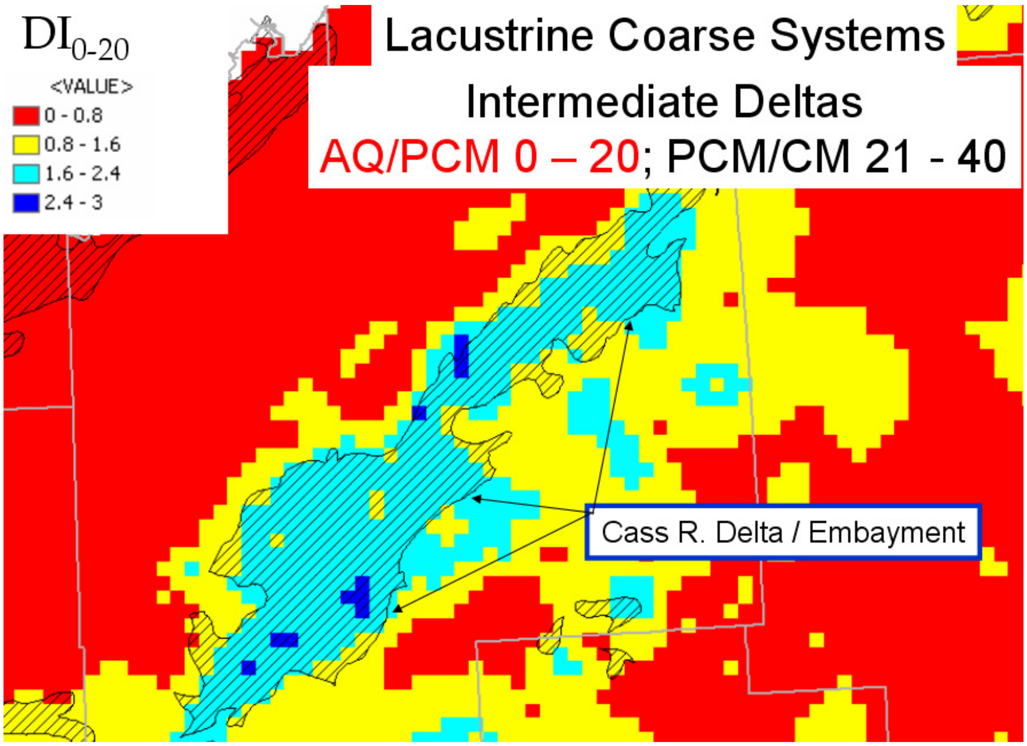

Figure 4.2.27a. Glacial Cass River delta – 0 to 20 ft. depth range.

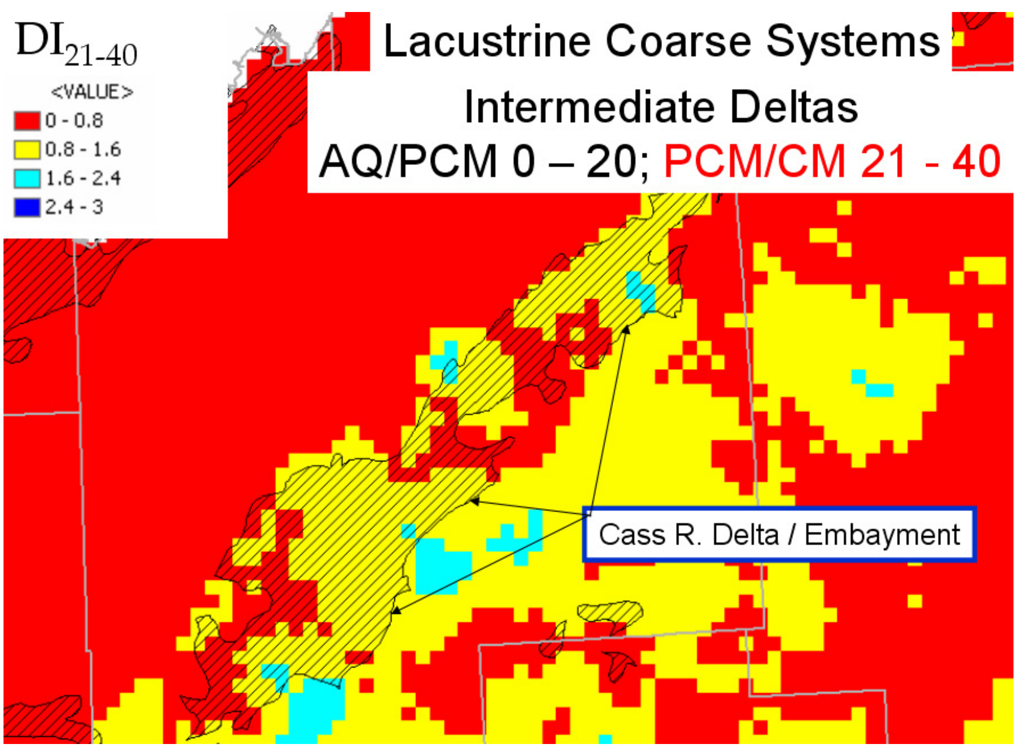

Figure 4.2.27a. Glacial Cass River delta – 21 to 40 ft. depth range.

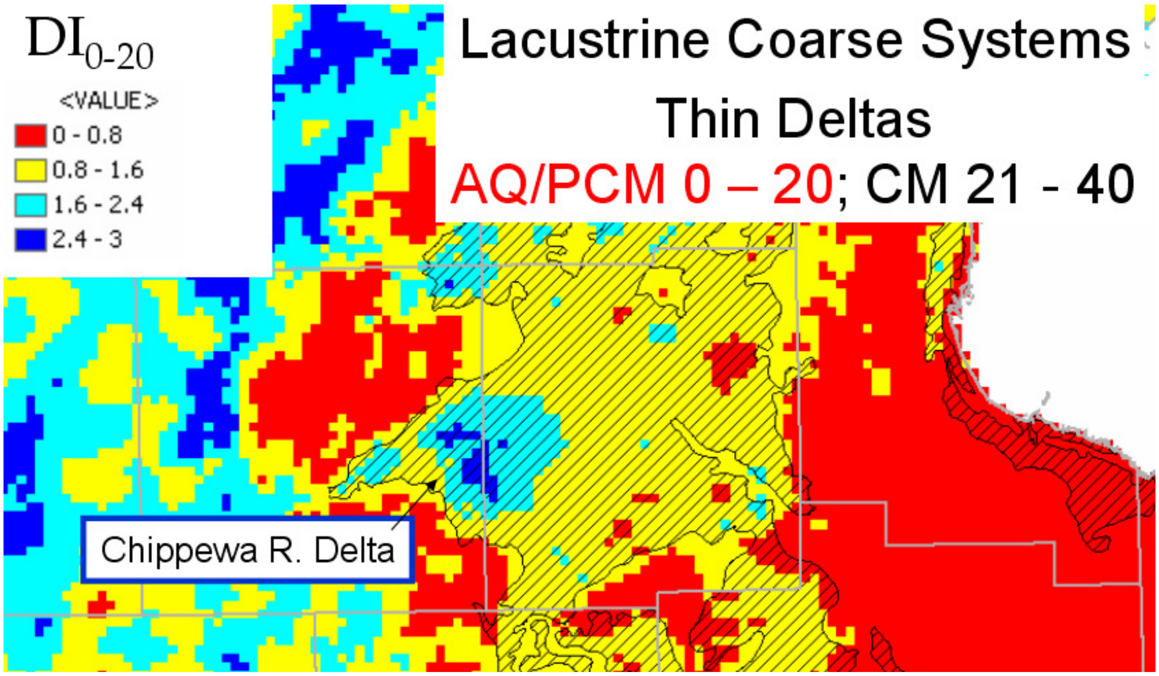

Figure 4..2.28a. Glacial Chippewa River delta – 0 to 20 ft. depth range.

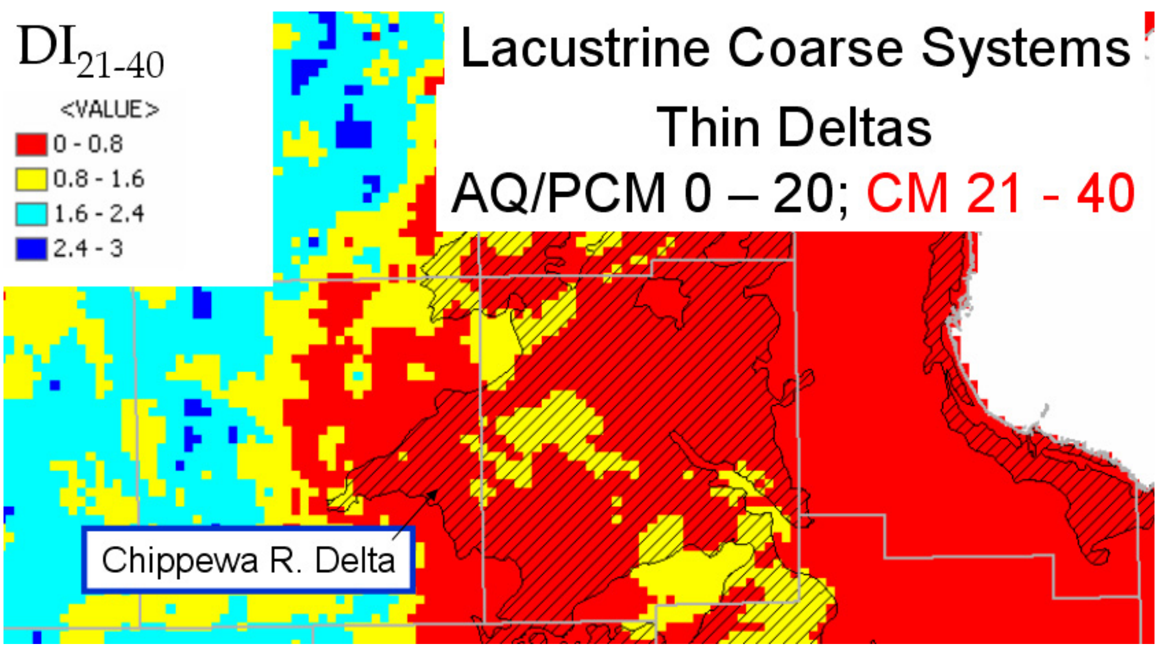

Figure 4..2.28b. Glacial Chippewa River delta – 21 to 40 ft. depth range.

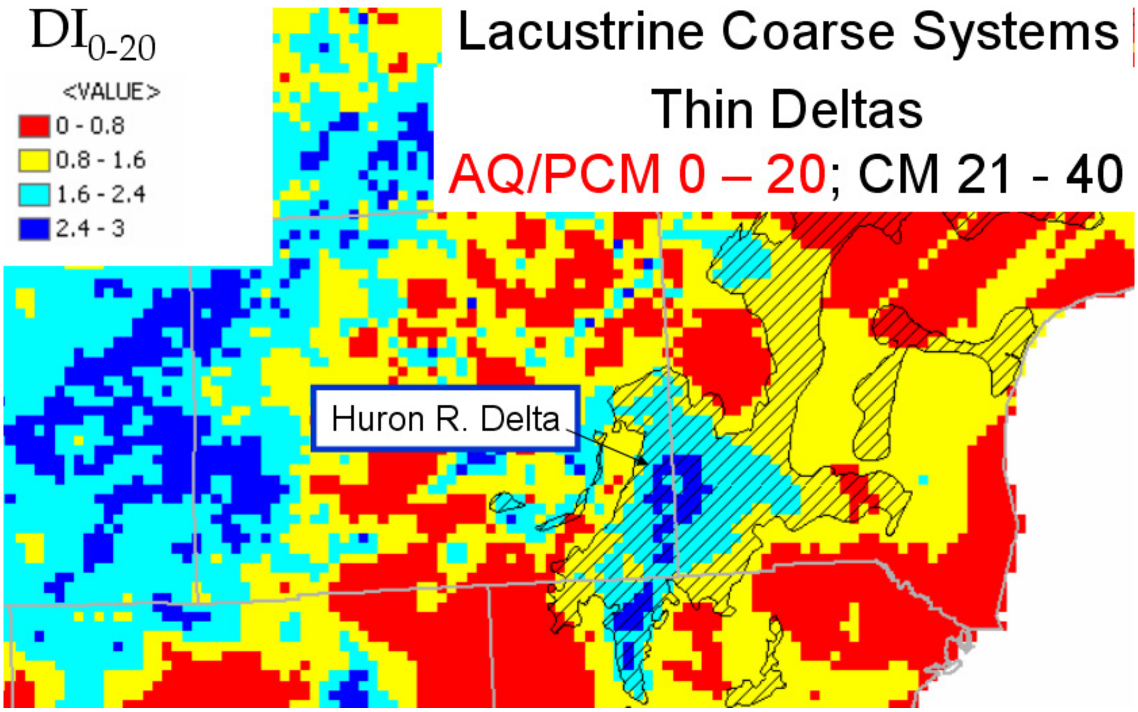

Figure 4.2.29a. Glacial Huron River delta – 0 to 20 ft. depth range.

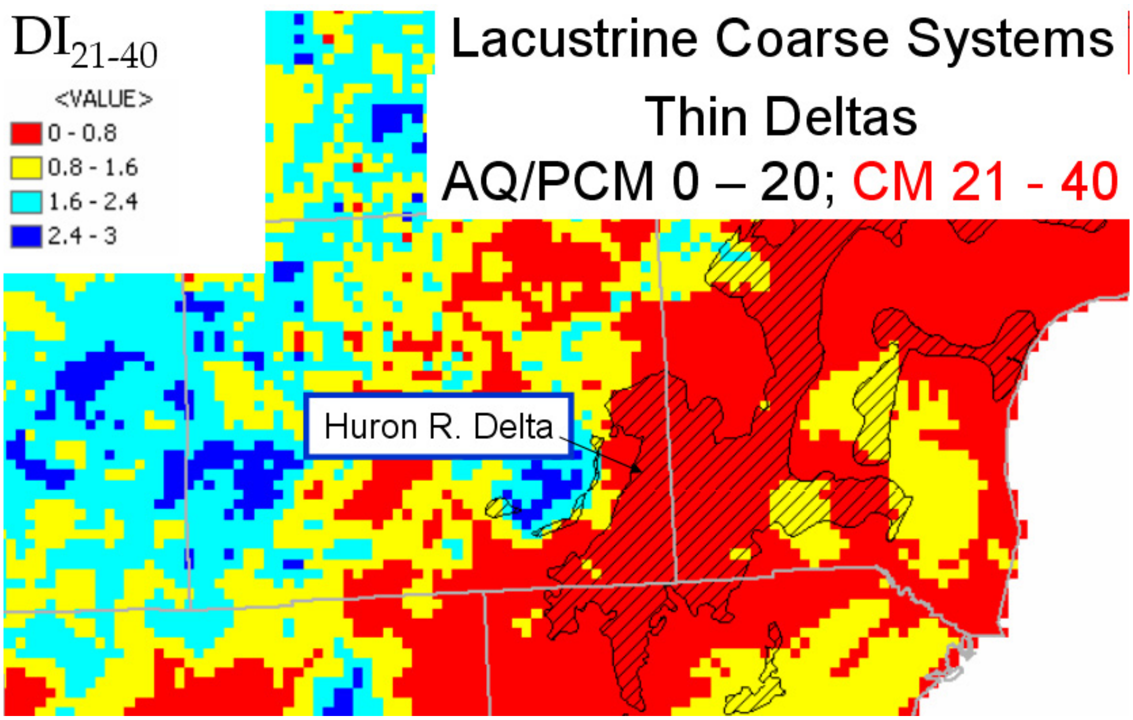

Figure 4.2.29b. Glacial Huron River delta – 21 to 40 ft. depth range.

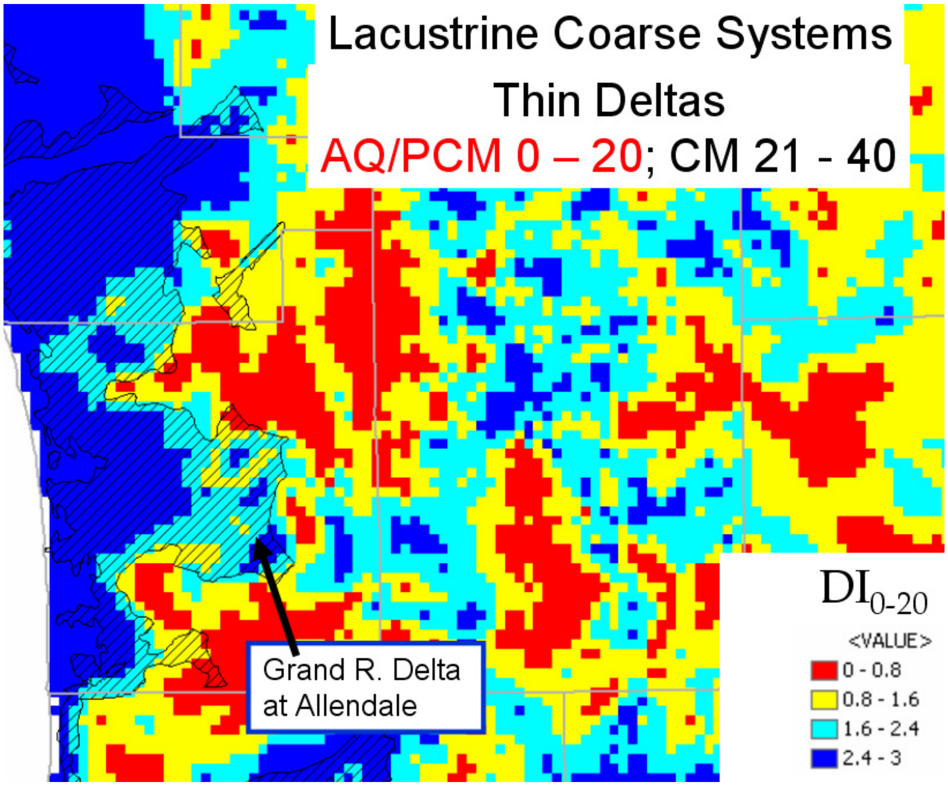

Figure 4.2.30a. Glacial Grand River delta – 0 to 20 ft. depth range.

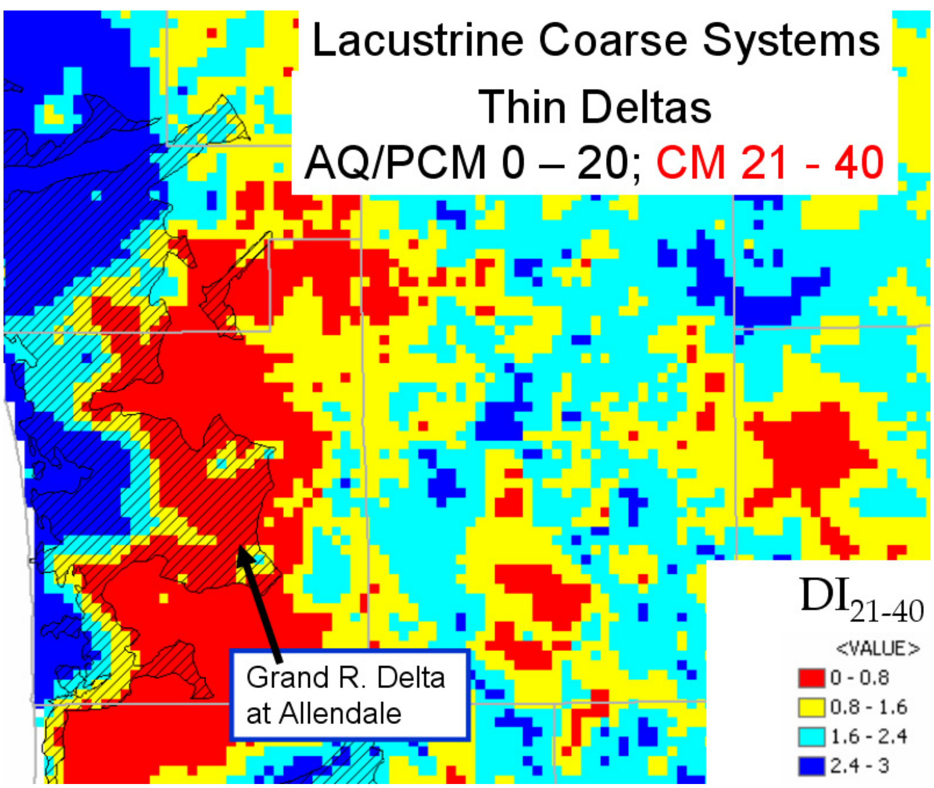

Figure 4.2.30b. Glacial Grand River delta – 21 to 40 ft. depth range.

4.2.1.4 Estimation of Equivalent Hydraulic Properties

Estimation of the equivalent horizontal and vertical hydraulic conductivities provides an evaluation of the entire usable *Wellogic* database (especially the lithologic data) in a manner similar to that used to calculate the Drift Index. This method is superior to the Drift Index approach because it assigns estimated hydraulic conductivity values to each lithology reported on the well record rather than an arbitrary scaler number as used for the Drift Index.

For a system with horizontal layers, the equivalent hydraulic conductivities are defined as (Freeze and Cherry, 1979):

$$K_h = \frac{\sum_{i=1}^{n} K_i B_i}{B} \qquad (4.2.2)$$

$$K_v = \frac{B}{\sum_{i=1}^{n} \frac{B_i}{K_i}} \qquad (4.2.3)$$

Where: B is the total thickness of the unit
B_i is the thickness of layer i
K_i is the hydraulic conductivity of layer i,
n is the total number of layers in the unit
K_v is the equivalent vertical hydraulic conductivity (flow perpendicular to the layers)
K_h is the equivalent horizontal hydraulic conductivity (flow parallel to the layers).

In general, the equivalent vertical hydraulic conductivity is controlled by the layer in the sequence with the lowest hydraulic conductivity, and the equivalent horizontal hydraulic conductivity is controlled by the layer with the highest hydraulic conductivity. For this study, only the horizontal hydraulic conductivity was used to calculate estimated yield and drawdown.

In the analysis, the estimates of equivalent hydraulic conductivity were made using the lithologies reported from the bottom of the well screen, or the top of rock for wells completed in bedrock underlying the glacial deposits, up to the static water level reported for the well. This choice limits the equivalent hydraulic conductivity estimate to the material within the saturated thickness of the aquifer. Glacial deposits exist below the level of well screens in most places in Michigan. Obviously, these lithologies are not incorporated into the analysis because they are not present on the water-well record. Only the used portion of the glacial deposits is evaluated in this analysis. This limitation may be important in areas of the State where the glacial deposits are thick and most wells only penetrate the top 100 to 200 ft. It may be possible to develop high-capacity wells by exploiting these deeper deposits, and groundwater use development of this type is not considered in the analysis for the yield estimates.

The equivalent hydraulic conductivities were estimated for the *Wellogic* records using an assigned value for hydraulic conductivity for each lithology. This assigned value was determined using a textbook range of values that had been adopted by the Source Water Assessment Program (MDEQ, 2004). The mean of the log(K) values of the range was assigned to each lithology. The ranges and assigned values are given in Table 4.2.1.

In addition to computing the equivalent hydraulic conductivities, the ratio of K_v to K_h was computed. This ratio indicates the degree of heterogeneous layering reported in the water-well record. If the K_v/K_h ratio is near one, the hydraulic conductivities for all the units in the record are approximately equal. If the ratio is very small, then K_v is much less

Table 4.2.1 Assigned range and geometric mean of the estimated hydraulic conductivity values for *Wellogic* lithologies in feet per day. NA – no value assigned.

Wellogic Lithology	Minimum Hydraulic Conductivity, feet per day	Maximum Hydraulic Conductivity, feet per day	Geometric Mean Hydraulic Conductivity, feet per day
BASALT	1.0×10^{-7}	10000	0.032
BOULDERS	1000	100000	10000
CLAY	1.0×10^{-7}	0.001	1×10^{-5}
CLAY & BOULDERS	1.0×10^{-7}	0.001	1×10^{-5}
CLAY & COBBLES	1.0×10^{-7}	0.001	1×10^{-5}
CLAY & GRAVEL	1×10^{-6}	0.001	3.2×10^{-5}
CLAY & SAND	1×10^{-6}	0.001	3.2×10^{-5}
CLAY & SILT	1.0×10^{-7}	0.001	1×10^{-5}
CLAY & STONES	1.0×10^{-7}	0.001	1×10^{-5}
CLAY GRAVEL SAND	1×10^{-6}	0.01	0.0001
CLAY GRAVEL SILT	1×10^{-6}	0.01	0.0001
CLAY GRAVEL STONES	1×10^{-6}	0.01	0.0001
CLAY SAND GRAVEL	1×10^{-6}	0.01	0.0001
CLAY SAND SILT	1×10^{-6}	0.01	0.0001
CLAY SILT GRAVEL	1×10^{-6}	0.01	0.0001
CLAY SILT SAND	1×10^{-6}	0.01	0.0001
COAL	1.0×10^{-7}	10	0.001
COBBLES	1000	100000	10000
CONGLOMERATE	1.0×10^{-7}	10	0.001
DEBRIS	NA	NA	NA
DOLOMITE	0.0001	10	0.032
DOLOMITE & LIMESTONE	0.0001	10	0.032
DOLOMITE & SANDSTONE	1×10^{-5}	10	0.01
DOLOMITE & SHALE	1.0×10^{-7}	10	0.001
DRYHOLE	NA	NA	NA
GRANITE	1.0×10^{-7}	10	0.001
GRAVEL	100	10000	1000
GRAVEL & BOULDERS	100	10000	1000
GRAVEL & CLAY	1.0×10^{-7}	0.001	1×10^{-5}
GRAVEL & COBBLES	100	10000	1000
GRAVEL & SAND	1	1000	32.
GRAVEL & SILT	0.1	1000	10
GRAVEL & STONES	100	10000	1000
GRAVEL CLAY SAND	0.0001	1	0.01
GRAVEL CLAY SILT	0.0001	1	0.01
GRAVEL SAND CLAY	0.01	10	0.32
GRAVEL SAND SILT	1	1000	32.
GRAVEL SILT CLAY	0.0001	1	0.01
GRAVEL SILT SAND	0.1	100	3.2
GREENSTONE	1.0×10^{-7}	10	0.001
GYPSUM	1.0×10^{-7}	10	0.001
HARDPAN	1.0×10^{-7}	0.001	1×10^{-5}
INTERVAL NOT SAMPLED	NA	NA	NA
IRON FORMATION	1.0×10^{-7}	10	0.001
LIMESTONE	0.0001	10	0.032
LIMESTONE & DOLOMITE	0.0001	10	0.032
LIMESTONE & SANDSTONE	1×10^{-5}	10	0.01
LIMESTONE & SHALE	1.0×10^{-7}	10	0.001
LITHOLOGY UNKNOWN	NA	NA	NA

Wellogic Lithology	Minimum Hydraulic	Maximum Hydraulic	Geometric Mean Hydraulic

	Conductivity, feet per day	Conductivity, feet per day	Conductivity, feet per day
LOAM	0.001	10	0.1
MARL	0.001	10	0.1
MUCK	0.001	10	0.1
MUD	0.001	10	0.1
NO LITHOLOGY INFORMATION	NA	NA	NA
NOLOG	NA	NA	NA
PEAT	0.001	10	0.1
QUARTZ	1.0×10^{-7}	10	0.001
QUARTZITE	1.0×10^{-7}	10	0.001
SAND	0.1	100	3.2
SAND & BOULDERS	0.1	100	3.2
SAND & CLAY	1×10^{-6}	0.1	0.00032
SAND & COBBLES	0.1	100	3.2
SAND & GRAVEL	1	1000	32.
SAND & SILT	0.01	1000	3.2
SAND & STONES	0.1	100	3.2
SAND CLAY GRAVEL	1×10^{-5}	1	0.0032
SAND CLAY SILT	1×10^{-6}	1	0.001
SAND GRAVEL CLAY	0.0001	1	0.01
SAND GRAVEL SILT	0.001	1	0.032
SAND SILT CLAY	1×10^{-6}	1	0.001
SAND SILT GRAVEL	0.001	100	0.32
SANDSTONE	1×10^{-5}	1	0.0032
SANDSTONE & LIMESTONE	1×10^{-5}	10	0.01
SANDSTONE & SHALE	1.0×10^{-7}	10	0.001
SCHIST	1.0×10^{-7}	10000	0.032
SEE COMMENTS	NA	NA	NA
SHALE	1.0×10^{-7}	0.0001	3.2×10^{-6}
SHALE & COAL	1.0×10^{-7}	0.0001	3.2×10^{-6}
SHALE & LIMESTONE	1.0×10^{-7}	0.0001	3.2×10^{-6}
SHALE & SANDSTONE	1.0×10^{-7}	10	0.001
SHALE SANDSTONE LIMESTONE	1.0×10^{-7}	0.0001	3.2×10^{-6}
SILT	0.001	10	0.1
SILT & BOULDERS	0.001	10	0.1
SILT & CLAY	1.0×10^{-7}	0.001	1×10^{-5}
SILT & COBBLES	0.001	10	0.1
SILT & GRAVEL	0.1	1000	10
SILT & SAND	0.1	100	3.2
SILT & STONES	0.001	10	0.1
SILT CLAY GRAVEL	1×10^{-6}	0.01	0.0001
SILT CLAY SAND	1×10^{-6}	0.01	0.0001
SILT GRAVEL CLAY	1×10^{-6}	0.01	0.0001
SILT GRAVEL SAND	1×10^{-6}	0.01	0.0001
SILT SAND CLAY	1×10^{-6}	0.01	0.0001
SILT SAND GRAVEL	0.001	100	0.32
SLATE	1.0×10^{-7}	10	0.001
SOAPSTONE	1.0×10^{-7}	10	0.001
STONES	100	10000	1000
TALC	1.0×10^{-7}	10	0.001
TOPSOIL	0.001	10	0.1
UNIDENTIFIED	NA	NA	NA
CONSOLIDATED FM			
VOID	NA	NA	NA

than K_h implying the presence of confining layers of low hydraulic conductivity interbedded with strata of higher hydraulic conductivity. Because K_v is dominated by the layer with the lowest hydraulic conductivity and K_h is dominated by the layer with the highest hydraulic conductivity, the ratio will never be greater than one.

Dot maps of equivalent K_h, equivalent K_v, and the K_v/K_h ratio are shown in Figures 4.2.31, 4.2.32, and 4.2.33. The patterns of equivalent horizontal hydraulic conductivity, similar to those shown by the Drift Index map, correspond to many of the general features shown in Plate 26, Aquifer Characteristics of Glacial Drift, of the Hydrogeologic Atlas of Michigan (Western Michigan University, 1981). Low equivalent hydraulic conductivities are depicted in southeastern Michigan, throughout the Saginaw Valley of east-central Michigan, and in the western Upper Peninsula (Figure 4.2.31).

A heterogeneous region trends southwestward from Saginaw Bay in which both the highest and lowest equivalent hydraulic conductivities are mapped. This trend corresponds to the glacial deposits formed by the Saginaw glacial lobe and may be indicative of the complicated heterogeneous depositional environment associated with regional ice stagnation where supraglacial and englacial outwash may be deposited locally within the finer-texture solifluction deposits. The northern portion of the Lower Peninsula of Michigan is dominated by moderate to high equivalent hydraulic conductivity values with very few well records reporting fine-texture lithologies. The most interesting features of the equivalent vertical hydraulic conductivity map (Figure 4.2.32) are the high values mapped in the northern Lower Peninsula and in west-central Michigan. The northern Lower Peninsula high values reinforce the pattern that few

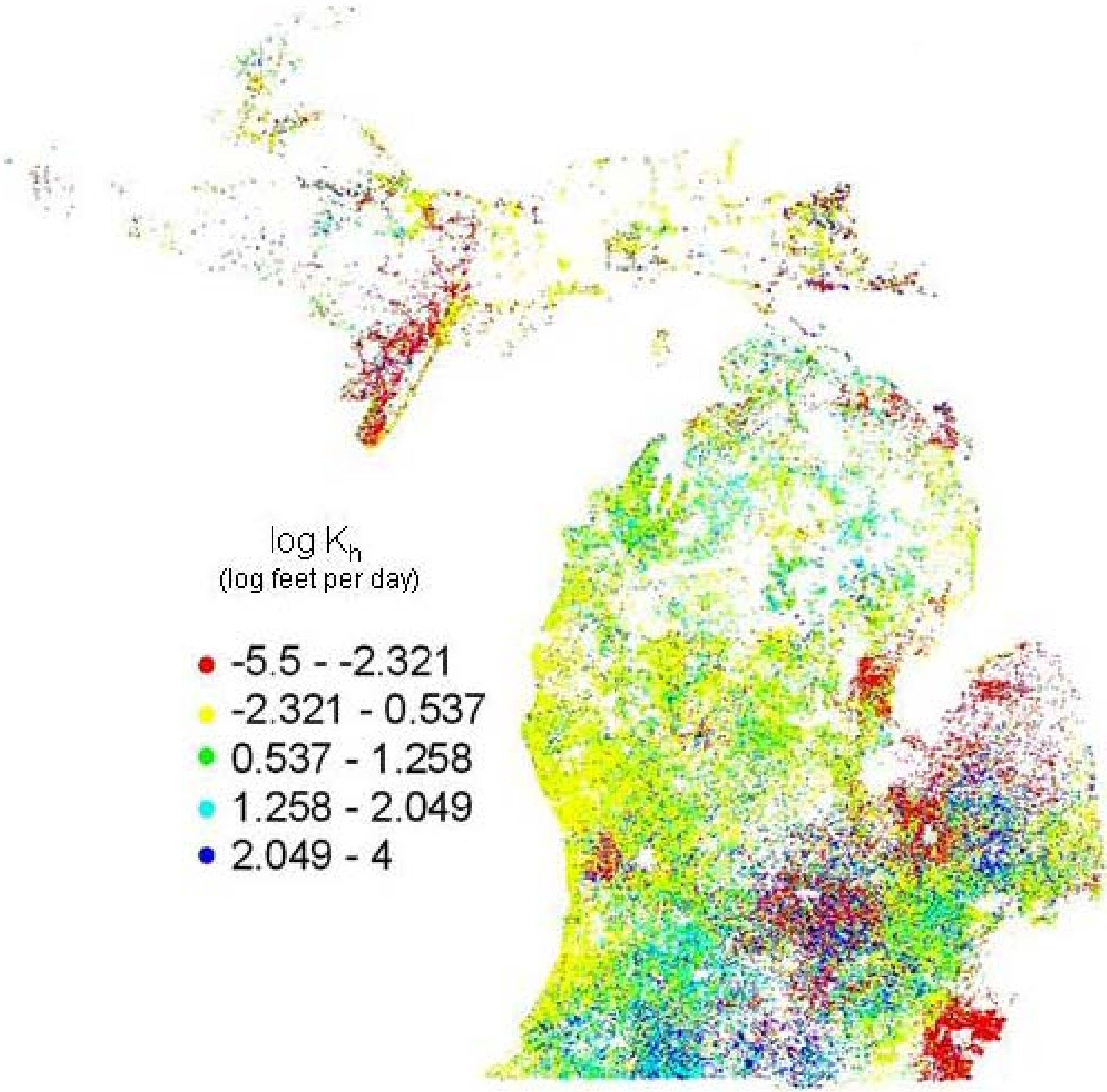

Figure 4.2.31. Log of the estimated equivalent horizontal hydraulic conductivity values (log of feet per day) for glacial deposits based on *Wellogic* lithologies and the geometric mean estimated hydraulic conductivity for each lithology as summarized in Table 4.2.1.

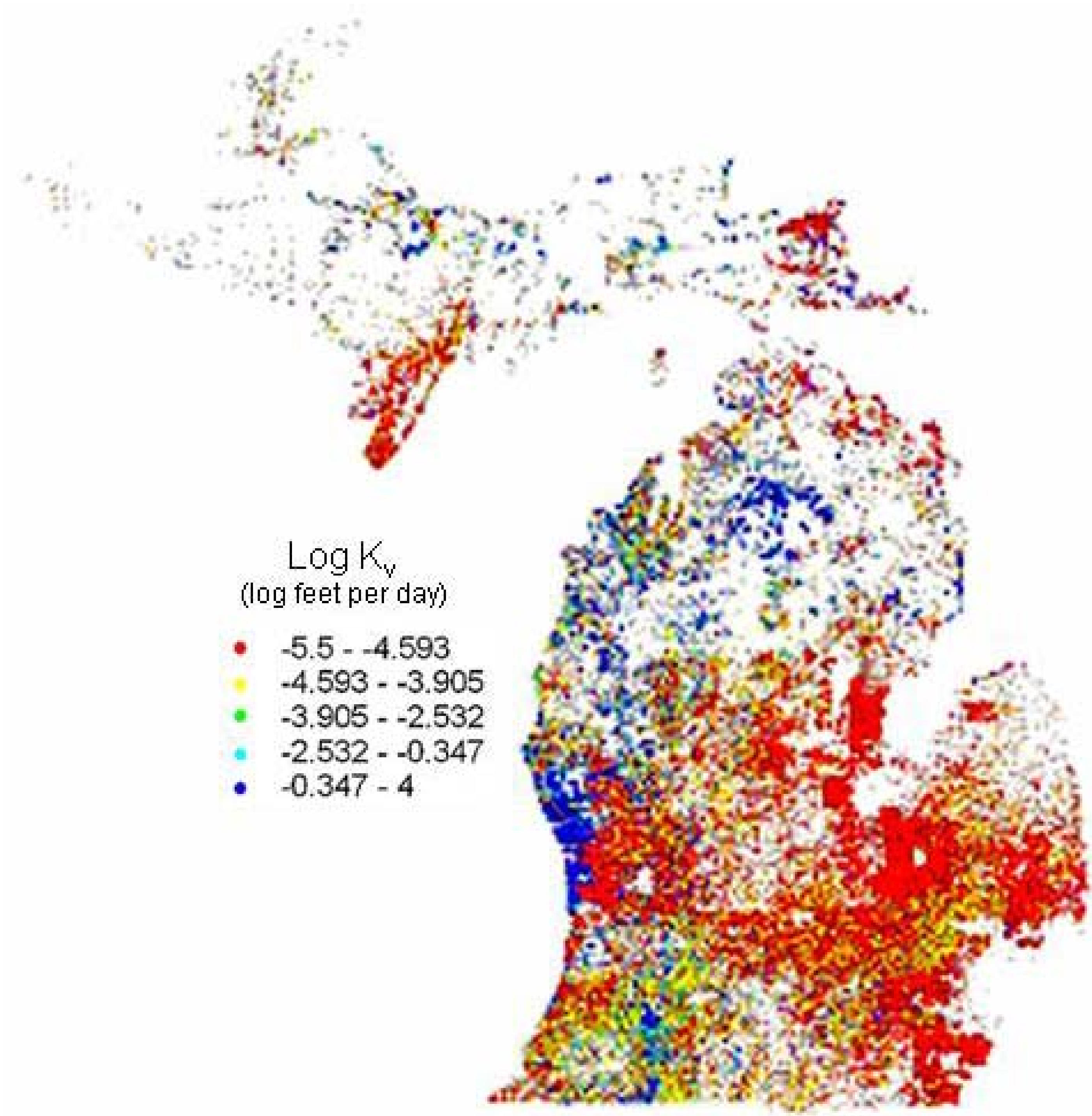

Figure 4.2.32. Log of the estimated equivalent vertical hydraulic conductivity values (log of feet per day) for glacial deposits based on *Wellogic* lithologies and the geometric mean estimate for hydraulic conductivity for each lithology as summarized in Table 4.2.1.

wells in this portion of the State encounter significant clay deposits. The high values in west-central Michigan result from a number of shallow wells that are completed in a sandy deposit that overlies a fairly continuous glacial clay. This clay overlies the Coldwater Shale confining unit at depth. Hence, the shallow sand aquifer is the first, and in many cases only, choice for residential wells in the area. The K_v/K_h ratio map (Figure 4.2.33) highlights regions of the state where well records provide uniform lithologies. The areas in west-central and northern Lower Michigan where K_v is high are evident. Ratios approaching one are also identified in southeasternmost Lower Michigan and intricately mixed with low values in the heterogeneous area of south-central Lower Michigan associated with the Saginaw drift. These well records are uniform, but may be mostly clay (i.e., they are bedrock wells).

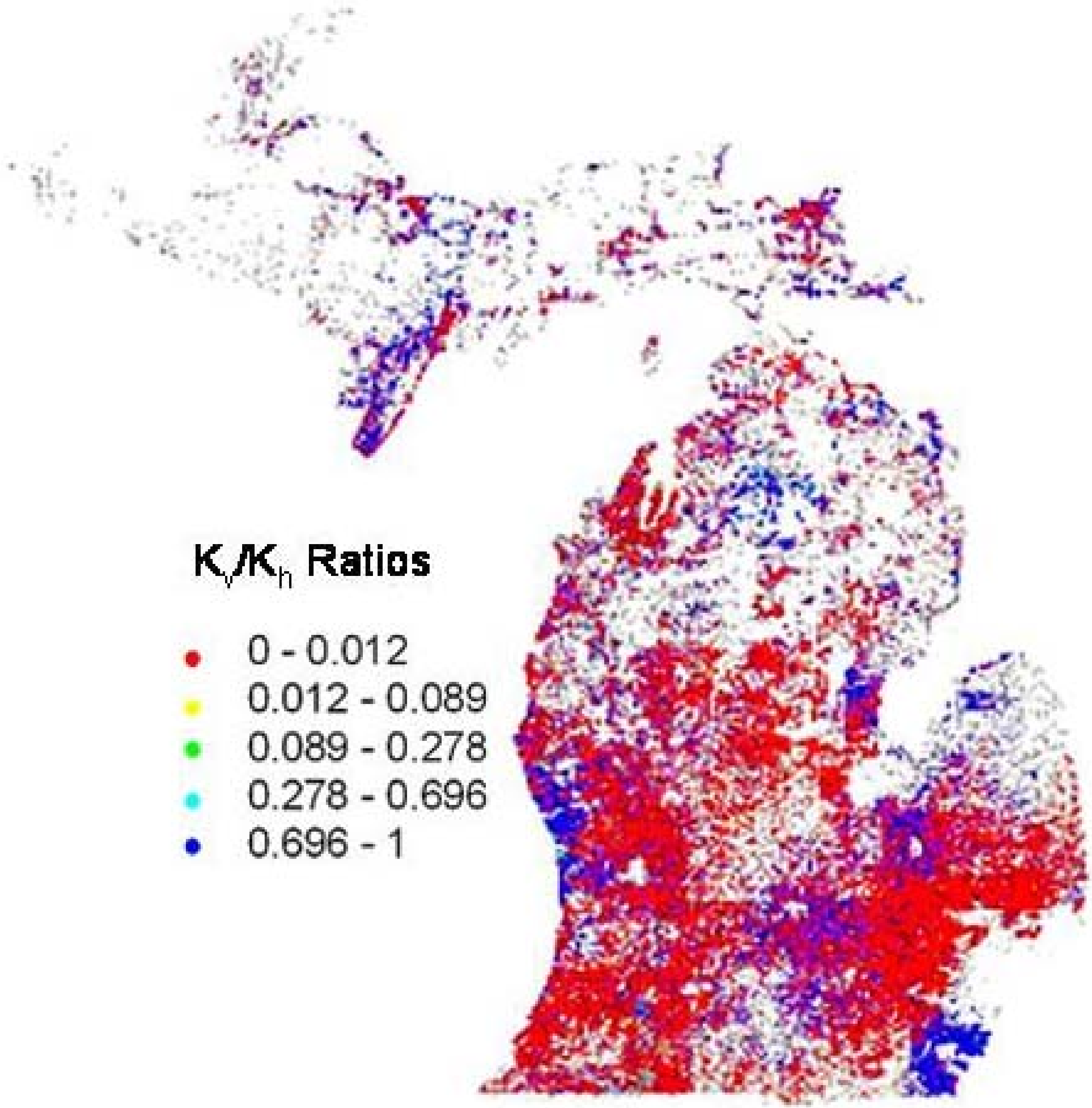

Figure 4.2.33. Ratio of estimated equivalent vertical hydraulic conductivity to estimated equivalent horizontal hydraulic conductivity based on *Wellogic* lithologies and the geometric mean estimate for hydraulic conductivity for each lithology as summarized in Table 4.2.1. Ratios near one indicate relatively uniform reported lithologies for a well record. Low ratio values indicate interbedding of aquifer material and confining material.

We assessed the degree of correlation between the estimated equivalent hydraulic conductivity values and the reported aquifer transmissivity in the P-1 database (described in Section 2.1). The hydraulic conductivity reported in the P-1 database was graphed along with all the equivalent horizontal hydraulic conductivity values estimated from the hydraulic conductivity values assigned to each lithology for well records in the *Wellogic* database that were from wells within 1000 m of the well from the P-1 database (Figure 4.2.34). For every P-1 data point, the well records within the 1000 m buffer reported lithologies with a wide range of equivalent hydraulic conductivities. No significant relation between the lithology-derived hydraulic conductivity and the hydraulic conductivity deduced from aquifer test data could be determined. Thus, although the general spatial patterns of estimated hydraulic conductivity appear reasonable, adjusting statewide values for hydraulic conductivity values for each lithology cannot reproduce the data from the P-1 database.

The computation of equivalent hydraulic conductivities provided an opportunity to count the lithologies reported in the well records. The resulting histogram of reported lithologies reveals a potential problem associated with relying on lithologic information to estimate hydraulic properties for glacial deposits: relatively few terms are used to describe the material encountered during drilling (Table 4.2.2). This observation is somewhat counter to the scatter in the estimated equivalent hydraulic conductivities shown in Figure 4.2.34. The scatter, however, is explained by the sensitivity of the estimate to changes in proportions of sand, gravel, and clay in the reported record, the wide range of hydraulic conductivity values assigned to each potential lithology, and the variation in depths observed for neighboring wells in many areas of the State.

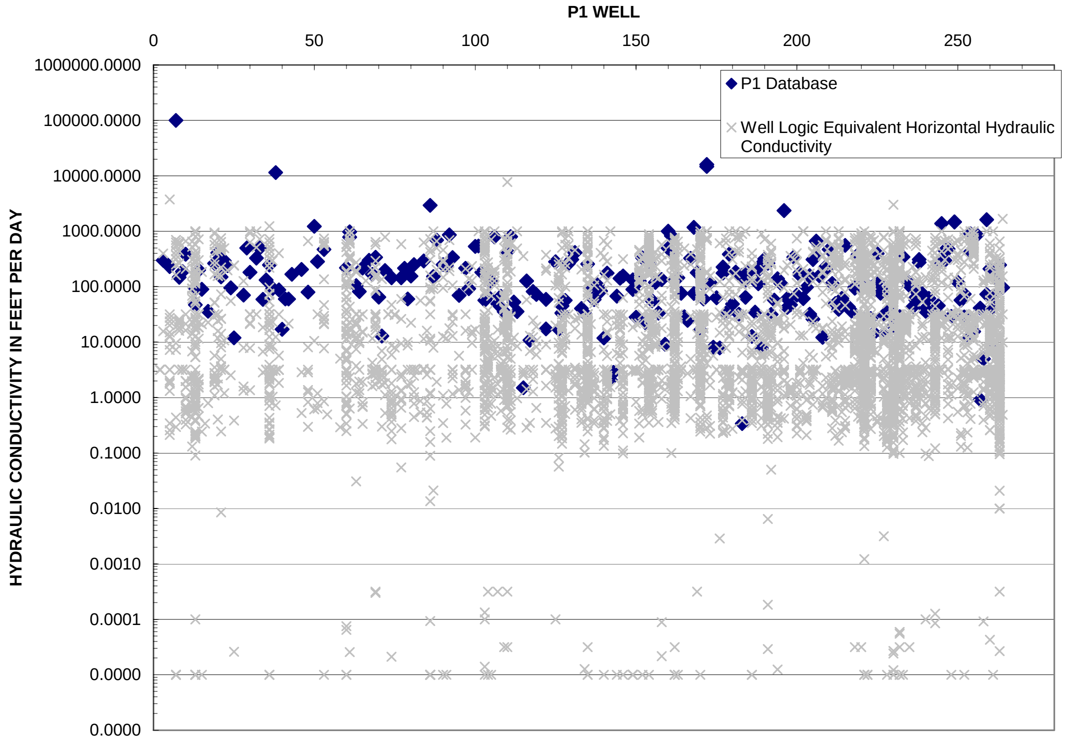

Figure 4.2.34. Hydraulic conductivity in feet per day derived from the P-1 database and the estimated equivalent horizontal hydraulic conductivities for wells within 1000 m of any P-1 well. Note the very wide range of estimated equivalent horizontal hydraulic conductivity around most wells.

The distribution of reported lithologies (Table 4.2.2) is clearly dominated by SAND and CLAY; these two terms are used orders of magnitude more than most other lithologies in the database. The inability to correlate aquifer-test transmissivity to lithology may be partially attributed to this use of only a few terms to describe the range of glacial deposits across the State. A single transmissivity for a lithology designation cannot capture the observed behavior because there is a fairly wide range in reported transmissivity values and relatively few lithologic terms. A second issue is that there may be regional bias in the use of lithologic terms. A driller in an area with low-yielding

Table 4.2.2. Count and cumulative feet of the top twenty reported lithologies in the *Wellogic* database. Well records missing information or with invalid locations in the *Wellogic* database were not used in this analysis. The total number of unique lithologies reported for the wells used in the analysis was 84.

LITHOLOGY	*COUNT IN SATURATED THICKNESS*	*FEET REPORTED IN SATURATED THICKNESS*
SAND	241767	4362210
CLAY	163968	4435163
SAND&GRAVEL	69889	1695520
GRAVEL	46219	722405
CLAY&GRAVEL	22984	594858
CLAY&SAND	18468	431715
SAND&CLAY	18439	384631
GRAVEL&SAND	8852	176751
HARDPAN	6638	170158
CLAY&STONES	5294	178574
GRAVEL&CLAY	4560	96671
SAND&STONES	3690	91609
SANDGRAVELCLAY	2611	60416
CLAYSANDGRAVEL	2414	64536
GRAVEL&STONES	1545	31902
TOPSOIL	1513	8420
SILT	1458	27604
CLAYGRAVELSAND	1354	37694
STONES	1239	15184
SAND&SILT	1076	21385

wells may refer to the best water-bearing strata encountered when drilling as SAND. That same material in a different part of the State may be referred to as SAND AND CLAY or SILT.

The *Wellogic* database contains secondary lithogy descriptors (see Table 8.8.1) such as FINE, COARSE, WITH CLAY, etc. To help refine the lithologic hydraulic properties, these lithology modifiers were considered by multiplying the geometric mean hydraulic conductivity assigned to each lithology by the hydraulic conductivity factor listed in Table 4.2.3. For example, the modifier W/ CLAY has a hydraulic conductivity factor of 0.1 which decreases the assigned hydraulic conductivity by an order magnitude. There were approximately 1700 unique combinations of primary and secondary lithologies. The twenty combinations that occurred most frequently are summarized in Table 4.2.3. Although this analysis helps include all the information provided by the driller, it did not change the ability to correlate lithology to transmissivities in the P-1 database and it did not change the overall statewide pattern of estimated equivalent horizontal hydraulic conductivity.

Table 4.2.3. The number of occurrences and the associated hydraulic conductivity factor for the top twenty reported modified lithologies in the *Wellogic* database. Well records missing information or with invalid locations in the *Wellogic* database were not used in the analysis. The total number of unique combinations of lithology and modifier reported for the wells used in the analysis was 1703. The hydraulic conductivity factor modifies (by multiplication) the base value of hydraulic conductivity assigned to a given lithology.

MODIFIED LITHOLOGY	COUNT	HYDRAULIC CONDUCTIVITY FACTOR
SAND FINE	39510	0.5
SAND COARSE	28616	2
SAND WET/MOIST	28548	1
CLAY SANDY	22740	10
SAND WATERBEARING	21646	1
SAND MEDIUM	20261	1
CLAY SOFT	13905	1
CLAY HARD	9750	1
SAND&GRAVEL COARSE	8528	2
SAND DRY	7698	1
GRAVEL COARSE	6821	1
SAND W/CLAY	6203	0.1
CLAY W/SAND	6112	10
SAND FINETOMEDIUM	6062	0.5
SAND W/GRAVEL	5869	1
CLAY W/GRAVEL	5572	10
GRAVEL FINE	4723	1
SAND MEDIUMTOCOARSE	4402	2
CLAY GRAVELY	3985	10

SANDSTONE W/SHALE	3874	0.1

4.2.1.5 Equivalent Hydraulic Conductivity by Landsystem

The equivalent horizontal hydraulic conductivity estimated using textbook ranges to relate reported lithology to hydraulic conductivity as given in Table 4.2.1 is expected to produce similar relation to landsystem as Drift Index because this method also is determined by the reported lithology. The range of values assigned, however, spans orders of magnitude from 10^{-6} for clay to 10^{+5} for gravel. The summary box-and-whisker plot shows that each landsystem has well records that give equivalent horizontal hydraulic conductivities over the entire possible range (Figure 4.2.35). The inner quartile spread for the lacustrine fine landsystem extends over six orders of magnitude. For each landsystem, the mean of the values is nearly two orders of magnitude larger than the median because of the assignment of hydraulic conductivities on the log scale and the presence of well records giving high hydraulic conductivities in each of the landsystems. As with the Drift Index, the lacustrine fine landsystem has the lowest median equivalent horizontal hydraulic conductivity. The medians for all the other landsystems, however, are very close to each other.

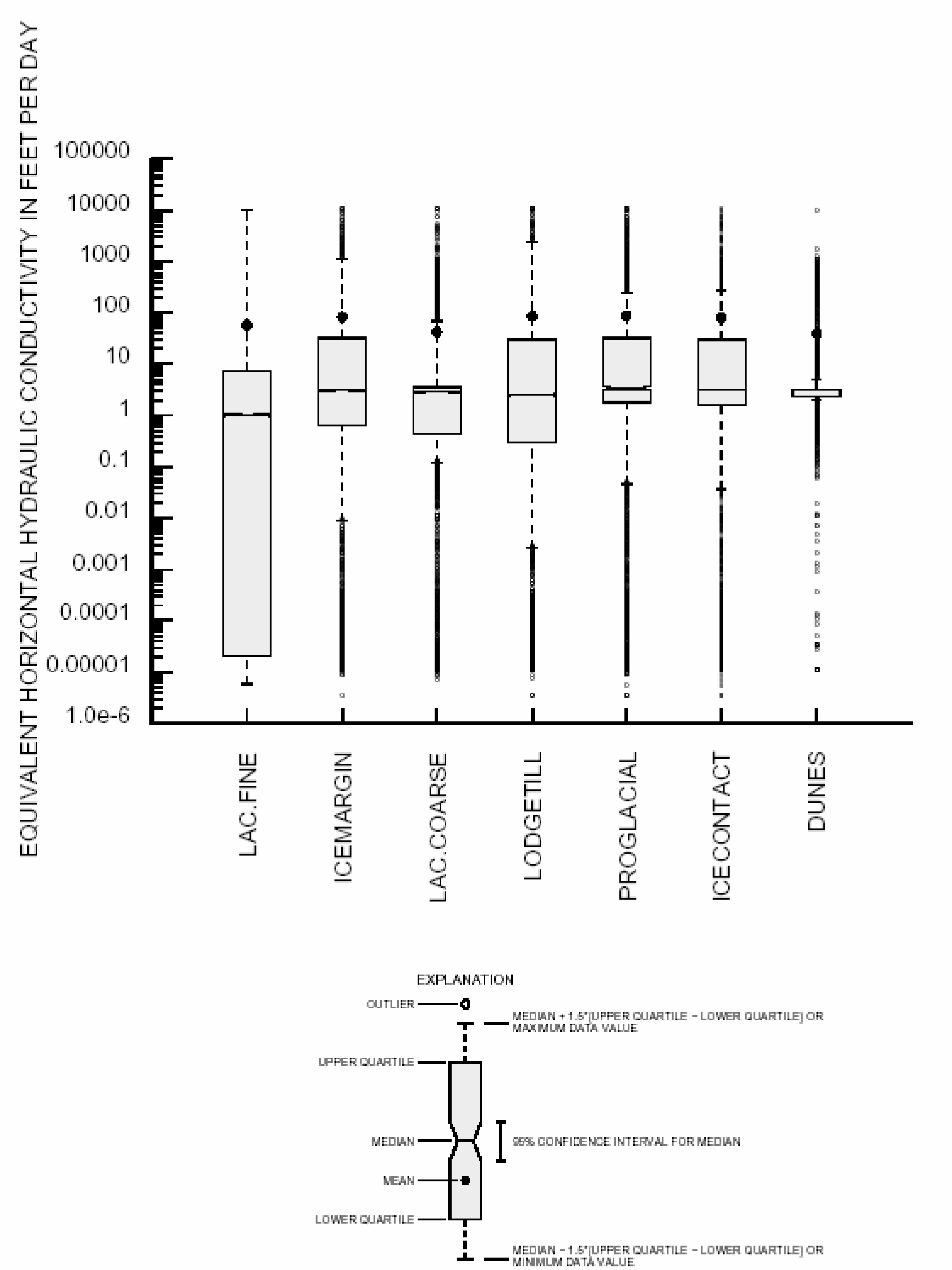

Figure 4.2.35. Distribution of equivalent horizontal hydraulic conductivity in feet per day by landsystem showing mean, median, 95% confidence interval for the median, upper and lower quartiles, and outliers beyond the mean ± (1.5*interquartile difference).

The semivariograms for this metric of potential aquifer behavior show less structure than those for the Drift Index (Figure 4.2.36). The semivariograms were constructed for the log(equivalent hydraulic conductivity) because this variable appears to be more log normal than normal for each of the landsystems. The coastal dunes and lacustrine coarse semivariograms show no structure, and the remaining landsystems indicate some structure with a range approximately 2000 ft. As in the Drift Index analysis, the uncertainty at zero separation distance is fairly large and is a large proportion of the overall variance of the property. These variograms indicate a high degree of variability at short distances.

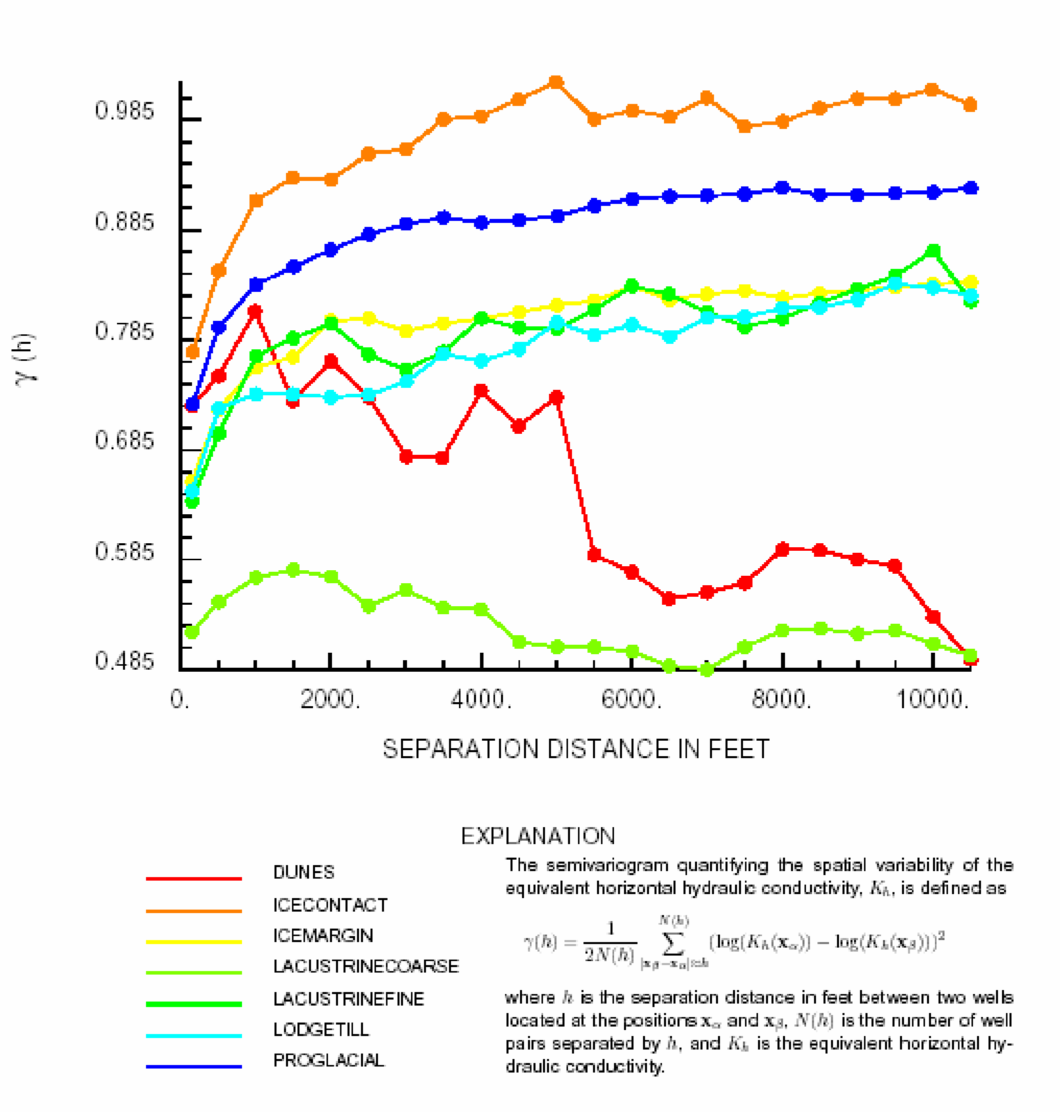

Figure 4.2.36. Semivariograms for log (equivalent horizontal hydraulic conductivity) for the glacial landsystems of Michigan.

4.2.1.6 Specific Capacity by Landsystem

The specific capacity analysis does not rely on lithology and, thus, may support the use of landsystems to influence the estimate of aquifer yield for the inventory and map. A box-and-whisker summary of the specific capacity by landsystem is given as Figure 4.2.37. Each landsystem exhibits a wide range in reported specific capacity values, and the mean is much higher than the median in all cases. The pattern noted in the Drift Index analysis also is indicated on Figure 4.2.37. The median specific capacity value is lowest for the lacustrine fine landsystem, The two till systems have the next lowest median values: ice marginal till and lodgement till. The remaining four landsystems have slightly larger median values: dunes, icecontact outwash, lacustrine coarse, and proglacial outwash. Although this pattern suggests differences between the landsystems, the maximum difference in median values is 369 and the range within each system is orders of magnitude. Although the medians are different to the 95% confidence level, the differences are small compared to the range of observed values. This analysis supports the notion that the general hydrogeologic behavior of glacial deposits in different landsystems is different, but only in a general sense. We suggest that the landsystems may be grouped into three groups exhibiting low Drift Index or specific capacity, intermediate Drift Index or specific capacity, and high Drift Index or specific capacity.

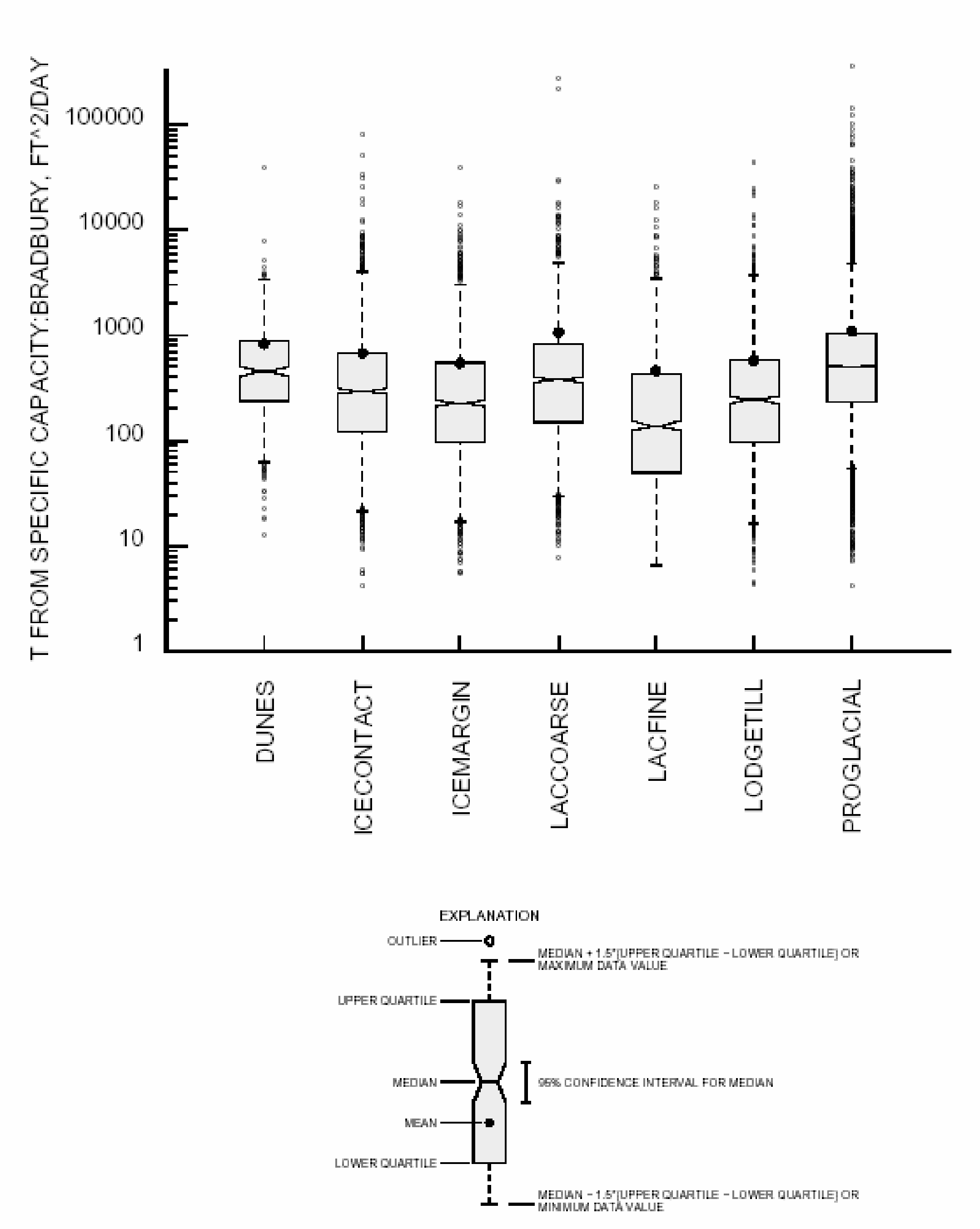

Figure 4.2.37. Summary of transmissivity as estimated from specific capacity using the Bradbury and Rothschild (1985) approach (see Section 4.2.1.5) showing the mean, median, 95% confidence interval for the median, upper and lower quartiles, and outliers beyond the mean ± (1.5*interquartile difference).

4.2.1.7 Aquifer Test (P-1) Values by Landsystem

The summary of the aquifer test transmissivities from the P-1 database classified by landsystem is presented as Figure 4.2.38. Because the sample size is much smaller for each landsystem, the uncertainty about the median is larger and more noticeable in this Figure. The medians 95% confidence intervals overlap for all of the landsystems. As expected from the previous results, the lacustrine fine median is the lowest and the proglacial outwash median is the highest. The overlap of values and wide range of observed transmissivity within each landsystem are troubling. As in the case of correlating lithology to the P-1 database, the correlation between landsystem and the P-1 database is not strong. Part of the lack of correlation may be due to the bias in the database towards wells that produce sufficient water for a public water supply. A second issue may be that the surficial landsystem may not always correspond to the relevant aquifer in the subsurface. Additional analyses were performed to determine if the landsystems map could be refined with emphasis on the water-producing intervals of the water well records from *Wellogic*.

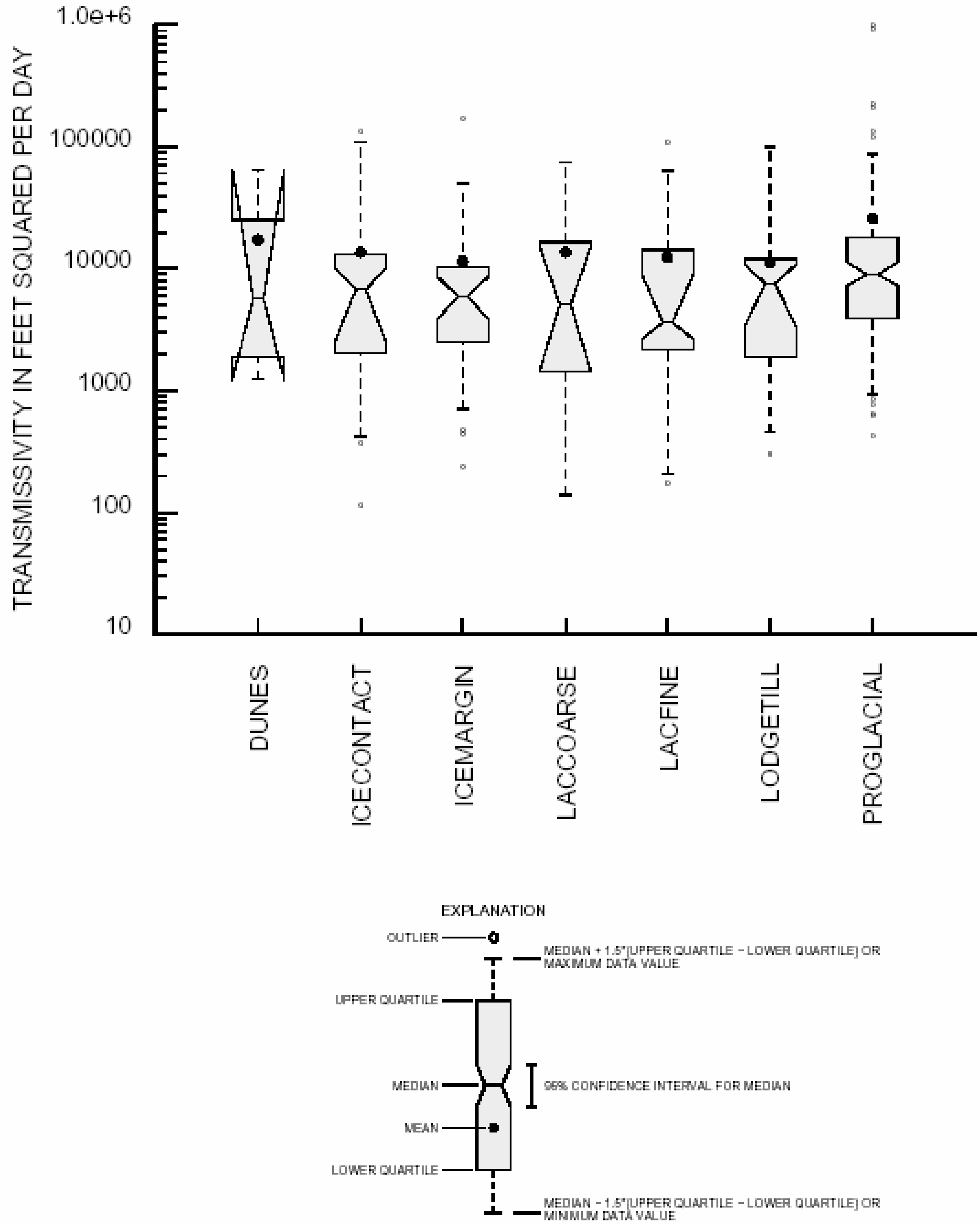

Figure 4.2.38. Summary of transmissivity as estimated from aquifer tests in the public water supply and well-head protection database showing the mean, median, 95% confidence interval for the median, upper and lower quartiles, and outliers beyond the mean ± (1.5*interquartile difference).

4.2.1.8 Summary of Landsystem Tests

The incorporation of the Landsystem map into the aquifer yield mapping process resulted from the inability of other methods that relied solely on information from the well records in the *Wellogic* database to capture the observed behavior of wells in the field. The major problem encountered with all these other methods is their overestimation of well yields in areas of the State where aquifer yields are known to be generally poor. Three reasons may explain these overestimations. The first reason is exploration bias in the P-1 database because wells with low yield are generally not developed to the point where an aquifer test is performed and a Public Water Supply System permit is sought from MDEQ. The second reason is the use of only a very few lithologic terms to describe the wide range of glacial deposits. In a region of the State where yields are typically poor, for instance, a poorly sorted, fine sand deposit with low yield may be reported on the water well record as SAND whereas the same term in other areas of the State denotes a well-sorted medium to coarse sand deposit with high yield. The third reason is that the reported lithologies at the well do not fully explain the behavior of the well. Local facies changes and discontinuities in three dimensions of the aquifer materials are also important to well yield. This type of information cannot be obtained from individual water well records.

The landsystem approach is our method of implementing the ideas of Anderson (1989) to identify the various glacial depositional environments as part of the yield estimation procedure. The analyses summarized above generally support the idea that water wells in different landsystems have different hydrogeologic characteristics, but they also suggest that the landsystems should be classified into three groups. The first group is composed of only the lacustrine fine landsystem and has the lowest anticipated transmissivities, the lowest Drift Index, the lowest equivalent horizontal hydraulic conductivity and the lowest specific capacity values. The second group has intermediate values of generalized transmissivity. This group contains the ice-marginal till, lodgement till or fine supraglacial drift, and lacustrine coarse landsystems. The third group has the highest anticipated transmissivity and includes the ice-contact outwash, proglacial outwash, and coastal dunes landsystems. Further differentiation between or within landsystems is not supported by the data and analyses used in this project.

4.2.1.9 Estimating Yield from Glacial Deposits

The approach used to estimate the yield from glacial deposits across the State addresses the two contrasting problems that plagued alternative methods that were based solely on *Wellogic* point data or that reclassified existing regionalizations: (1) point interpolation methods that do not recognize the regional glacial depositional settings fail to generate yield estimates that correspond with field experience, especially in areas of the State where water well yields tend to be low; (2) broad-area mapping approaches (e.g., reclassifying the glacial map or the glacial landsystem map), on the other hand, do not capture the observed heterogeneity in yield from glacial deposits and existing statewide yield maps tend to give only qualitative, not quantitative, information regarding aquifer yield. The approach combines the glacial landsystem map developed in this project with information from the *Wellogic* database to produce a quantitative estimate of aquifer yield. Our operational approach combines the glacial landsystem map developed for this project (see Chapter 3), with detailed information computed from the *Wellogic* database to produce quantitative estimates of glacial aquifer yield. The glacial landsystem map provided regional information that classified the State into areas where the anticipated transmissivity is low, intermediate, or high. Individual lithologies reported in the *Wellogic* database were used to develop equivalent hydraulic conductivity and transmissivity estimates that quantified the expected yield and captured the spatial heterogeneity within each landsystem. The steps in this process include:

1. Extract well record data from the *Wellogic* database. As part of the extraction program, the well location is checked, the elevation of the well based on the available digital elevation model (DEM) for the State is determined, and the percent aquifer material and Drift Index values are computed for both the saturated thickness and the various depth zones. The result of this program is a shapefile (ESRI, 1998) and an associated database characterizing the lithologic information (i.e., the MAQTYPE field).
2. Identify the glacial landsystem associated with the location of each water well record (Chapter 3).
3. For each well, assign hydraulic conductivity values for each lithologic layer reported in the water well record based on glacial landsystem and modified lithology classification. The hydraulic conductivity values assigned for each lithology by landsystem are summarized in Table 8.9.1, which is shown in the appendix chapter. The modifications of the hydraulic conductivity based on the lithology modifier were summarized in Table 4.2.3.
4. Compute the equivalent hydraulic conductivity for each well as described in Section 4.2.1.5.
5. Compute the estimated transmissivity for each well by multiplying the saturated thickness of the well (the distance from the bottom of the well screen to the reported static water level) times the equivalent hydraulic conductivity calculated in step 4. Note that in areas of the State where the glacial deposits are thick, the

transmissivity estimate is only based on the portion of the deposits penetrated by water wells and reported on the water well records.

6. Apply a simple analytical equation (Theis solution) (Freeze and Cherry, 1979) to estimate the pumping rate that would be required to lower the hydraulic head at the well to fifty percent of the available drawdown after 100 days of pumping. This estimated discharge is computed using the transmissivity for the well from Step 5; the saturated thickness from the well record (the distance from the bottom of the well screen to the reported static water level) and a storativity value set at 0.0016, which is typical of a leaky-confined aquifer.
7. For all wells within each of the three landsystem groups (low, moderate and high transmissivities, see Table 8.9.2), apply ordinary Kriging to the data at each well to interpolate both transmissivity and yield to 1000 m x 1000 m grids.
8. Assemble statewide transmissivity and yield maps from the Kriged estimates for each landsystem group (Figure 4.2.39 and 4.2.40).
9. Identify areas where the glacial deposits are less than 30 feet thick and identify zones that are more than 2000 m away from any well in the *Wellogic* database. Overlay both of these factors on the transmissivity and yield maps.
10. Use the analytical expression (Theis solution, Freeze and Cherry, 1979) to estimate the change in the hydraulic head within the aquifer at a distance of 500 feet from a proposed well pumping at the yield value for each grid cell (Figure 4.2.41). This drawdown map can be used to estimate the impact on the aquifer caused by a hypothetical well being pumped at the estimated yield. This drawdown is only a general estimate and should not be used for regulatory purposes, especially because it does not account for the impacts of multiple

pumping wells within each grid cell and the hydraulic nuances of the aquifer that only can be obtained through the analysis of an aquifer test.

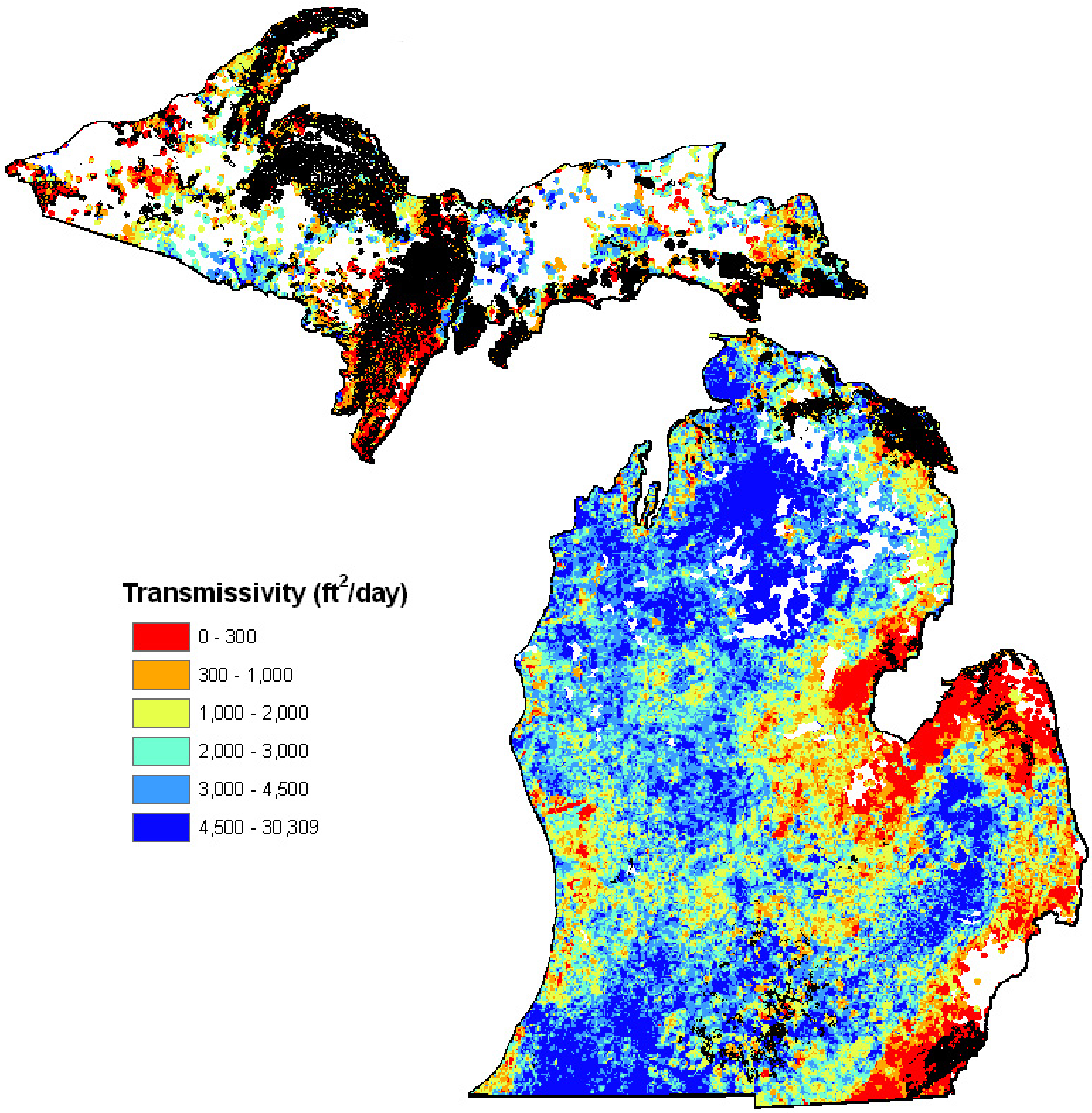

Figure 4.2.39. Estimated transmissivity for the glacial deposits of Michigan. Transmissivity is estimated using estimated hydraulic conductivity values for each lithology reported in the *Wellogic* database based on the landsystem for the well identified using the Glacial Landsystems map. Only the saturated thickness of the glacial deposits reported in the well records is used in this estimate.

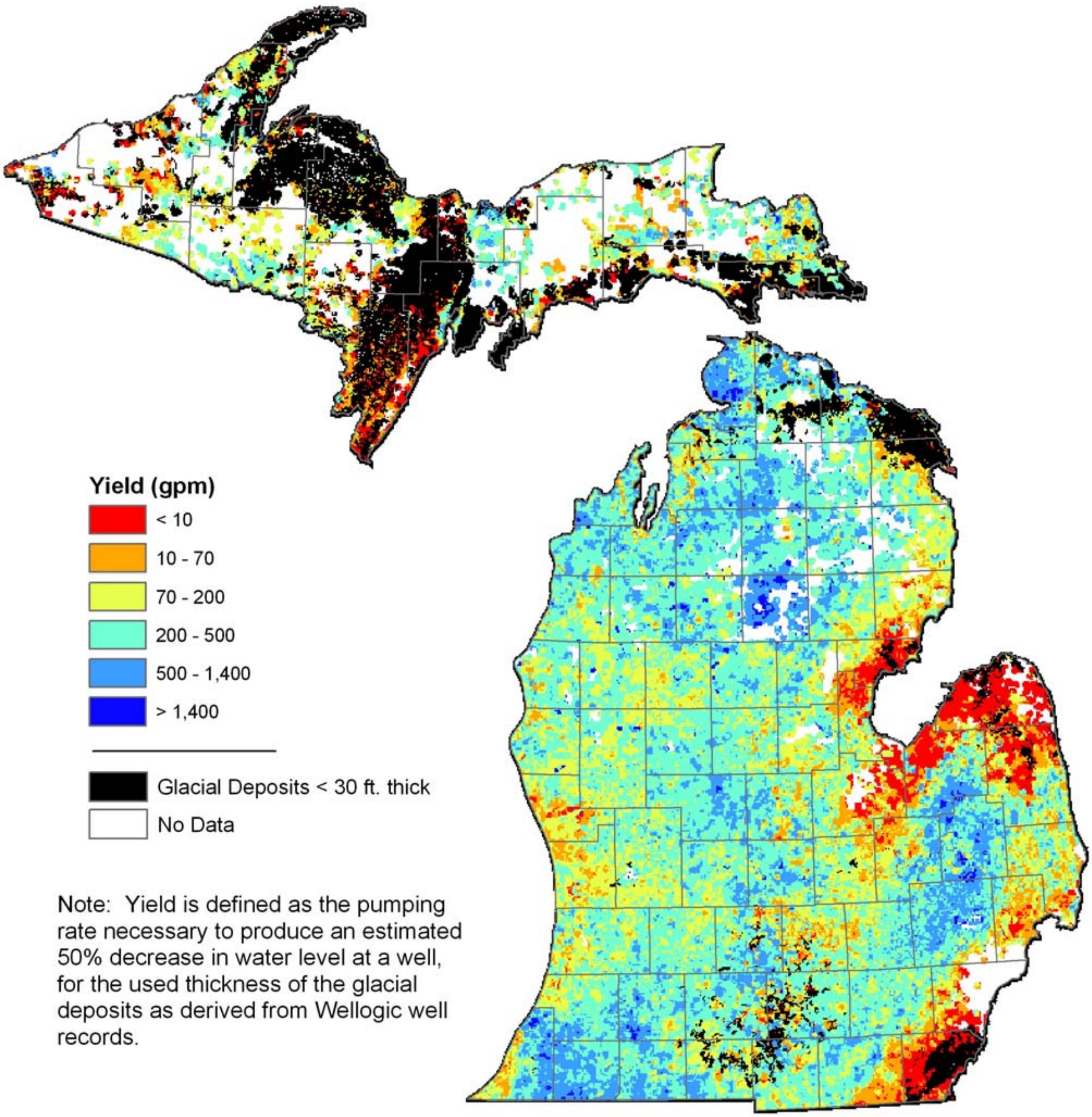

Figure 4.2.40. Estimated groundwater yield from the glacial deposits of Michigan. Yield is the estimated pumping rate required to cause a fifty percent reduction in water level at the well as calculated using the Theis analytical solution.

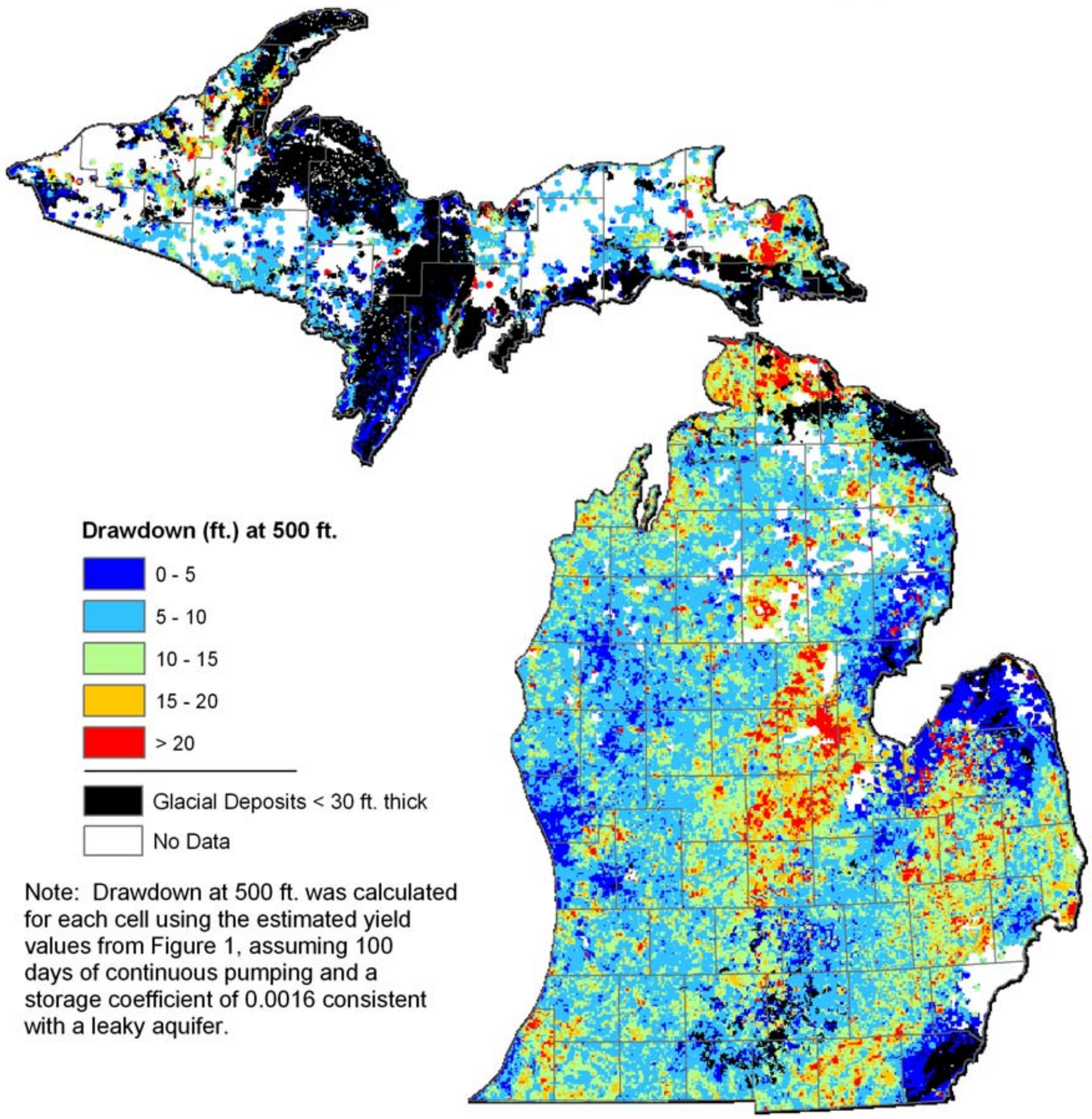

Figure 4.2.41. Estimated change in the hydraulic head within the aquifer at a distance of 500 feet from a proposed well pumping from the glacial deposits of Michigan at the estimated yield value for each grid cell. Yield is the estimated pumping rate required to cause a fifty percent reduction in water level at the well as calculated using the Theis analytical solution.

4.2.2 Bedrock Aquifers

Four major sources of hydrogeologic data were available for the delineation of bedrock aquifer properties. These were 1) the aquifer test archive maintained by the MDEQ (the P-1 database), 2) the aquifer test database developed by the USGS Regional

Aquifer System Analysis (RASA) for the Michigan Basin, 3) hydraulic properties taken from a published series of county hydrogeologic reports and 4) specific capacity data from a subset of wells in *Wellogic* database.

The MDEQ aquifer test archive is a compilation of all aquifer tests submitted to the MDEQ as part of the permit process for new municipal water supplies and those tests submitted as a component of wellhead protection area delineations. The aquifer test archive database created by the Michigan Basin RASA was a compilation of aquifer test records from throughout the state that were on paper files with the Michigan Geologic Survey (MGS). The county hydrogeologic reports were a cooperative project between the MGS and the USGS that describe the hydrogeologic framework of many individual counties in Michigan. Often these reports contain estimates of the hydraulic properties of aquifer materials. Lastly, the *Wellogic* system is a database containing over 400,000 digital water well records. Only *Wellogic* records with valid location and lithology data were used for this study.

Initially, only the MDEQ aquifer test archive, the RASA aquifer test database, and the county hydrogeologic summaries were used to compile transmissivity data for the bedrock aquifers in the state. Transmissivity values reported in the RASA database and the county hydrogeologic summaries with valid location information were entered into a spreadsheet, which was then converted to an ESRI shapefile and merged with the MDEQ aquifer test archive shapefile. The transmissivity estimates were then sorted and separated based on the aquifer unit associated with the test. These aquifer designations for each well were cross-referenced with the bedrock geologic map (Milstein, 1987), and with the Michigan Basin RASA hydrostratigraphic unit thicknesses, where available (Westjohn and Weaver, 1998).

For most of the bedrock units studied (all except the Saginaw and Marshall aquifers), there were not enough transmissivity data from the MDEQ aquifer test archive, the RASA aquifer test database, or the county groundwater summaries to interpolate transmissivity across the areal extent of the unit. In those cases, wells in the *Wellogic* database that had specific capacity data were used to estimate transmissivity. Specific capacity of a well is defined as its yield per unit drawdown. This value is obtained by dividing the discharge for a well by the drawdown caused by that discharge. Such data are often recorded at the time a well is installed on the well record.

Only bedrock wells from the *Wellogic* shapefile that had recorded information about the duration of the pumping, pumping rate, radius of the well, or drawdown caused by pumping and that had determined specific capacity by test pumping or bailing were used for this analysis. After the set of wells with the correct input information was established, the specific capacity data were imported into the MATLAB software package (MathWorks, 2004). Because the storage coefficient (S) was not measured or recorded, a constant value of 0.0004 was used for all calculations. The equation relating specific capacity to transmissivity is nonlinear, so a Newton-Raphson code for MATLAB (Constantinides and Mostoufi, 1999) was needed to iteratively solve the equation to estimate transmissivity for the aquifer. This procedure was done for each of the selected wells and the resulting transmissivity estimates were appended to the *Wellogic* shapefile, which was then sorted and separated by bedrock aquifer unit following the procedure used earlier. The result was a separate shapefile of transmissivity estimates (derived from specific capacity data) for each rock unit, with the exception of the Saginaw and Marshall aquifers. These shapefiles were combined with the existing transmissivity shapefiles developed from the MDEQ aquifer test archive, the RASA aquifer test database, and the county summary data. Finally, all transmissivity data were grouped by bedrock aquifer unit and used as inputs for transmissivity interpolation.

The Groundwater Modeling System (GMS), a pre-processing/post-processing program for MODFLOW was used to interpolate the point transmissivity estimates for each aquifer. GMS has a geostatistical module that readily accepts GIS inputs and can export GIS files as well. The first step of this process was to define the extent of the aquifer, which was done by extracting an ESRI shapefile from the digital bedrock geology map of Michigan (Milstein, 1987) for the bedrock unit of interest. A grid was then generated using a 1000 m grid cell spacing and overlain on the aquifer extent shapefile. The point shapefile of aquifer test transmissivity estimates was imported into GMS as a 2D scatter point file. The inverse-distance-weighted (IDW) algorithm (GMS 4.0 Online Help Manual, 2003) was used to interpolate the transmissivity estimates to the grid because the sparse data sets available did not support the use of the Kriging algorithm (GMS 4.0 Online Help Manual, 2003). IDW is a conservative spatial interpolator tat produces continuous surface values that are always within the range of the input data and which approach the average value of the data set in areas distant from control points. Once the transmissivity estimates were interpolated to a grid, it was exported into the ESRI ArcGIS environment.

As a result of having to interpolate transmissivity values over large areas with few data points, a 20,000-meter buffer zone was established around the well points. Portions of the bedrock aquifer that were outside the buffer zone (i.e., further than 20 km from a data point) were uniquely symbolized to highlight the potential error associated with the estimated transmissivity values.

In some situations, there were too few data points to adequately interpolate transmissivity. This was the case with the Middle Devonian carbonates underlying the northern tip of the Lower Peninsula. Here, no interpolation was attempted. Instead, the few estimates of transmissivity that were available were shown as point data. No interpolation was attempted in portions of the western Upper Peninsula, where transmissivity is controlled by fractures in the metamorphic and volcanic rocks that compose the bedrock aquifer.

Following the transmissivity determination for each bedrock unit, the available drawdown for each unit was estimated by subtracting the depth to water in a well from the depth of the well. If the static-water-level or depth for a well was not available in the *Wellogic* records, that well was not used in the analysis. The resulting available drawdown shapefile was imported into GMS as a 2D scatter point file. In this case, ordinary Kriging was used to interpolate the available drawdown data because there were a large number of data points. The available drawdown was then interpolated to the same grids used for the transmissivity interpolations.

Once estimates of transmissivity and available drawdown were mapped to a corresponding bedrock unit, the Theis solution for aquifer tests was used to solve for discharge from that bedrock unit. The MATLAB programming environment was used to develop a code that solved the Theis equation using Arc ASCII grids as inputs.

For the case of the bedrock discharge estimation, the ASCII grid of the bedrock unit's transmissivity (T) was read into MATLAB along with an ASCII grid of the available drawdown (s). The values used for S, t, and r were set to constants of 0.0004, 100 days, and 1 ft. Then for each cell, the discharge was computed that would cause a 50% decrease in the water level at the hypothetical discharge point, or half the available drawdown of the aquifer. The resulting discharge values were output as an Arc ASCII grid.

Following the calculation of the discharge grid, the code that solved the Theis equation was modified to solve for drawdown. The code then used the discharge grid calculated previously along with the transmissivity grid to estimate drawdown 500 ft from a hypothetical discharge point. Again, variables *S, t,* and *r* were held constant at values of 0.0004, 100 days, and, this time, 500 ft. The calculated drawdown values were then output as an Arc ASCII grid.

The drawdown modeled by this approach simulates the effect that pumping one new well in each cell at the estimated yield rate will have in that cell with no other new well influences. This program does not model what would happen if there were multiple wells pumping in different areas simultaneously.

Following the development of the ASCII grids for transmissivity, available discharge, and drawdown at 500 ft from a hypothetical discharge point, the grids were converted to the ESRI grid format using ArcINFO. For each bedrock unit, a new polygon coverage was created based on the extent of the bedrock unit's use. For some cases, this was just the subcrop area taken from the bedrock geologic map (Milstein, 1987). However, in many cases in the eastern Upper Peninsula, the outline extended to the rock units outside the subcrop area. For those cases, well records, county hydrogeologic summaries and personal communication with local MDEQ engineers (Charles Thomas, personal comm., 2005) assisted in delineating where aquifers were used outside of their subcrop area. Once a polygon coverage was established, it was converted to an ESRI grid. This new outline grid was then used as a template grid, into which data from the transmissivity, estimated yield, and drawdown grids were mapped.

The estimated grid values that fell outside of the template grid were masked and set to no data values. The result of this process was a set of grids with estimated values that were confined to the extent of each bedrock aquifer.

The estimated transmissivity for the bedrock aquifers of the state is shown in Figure 4.2.42, while the estimated yield for these aquifers is displayed in Figure 4.2.43. Figure 4.2.44 presents the estimated drawdown at 500 ft for the bedrock aquifers.

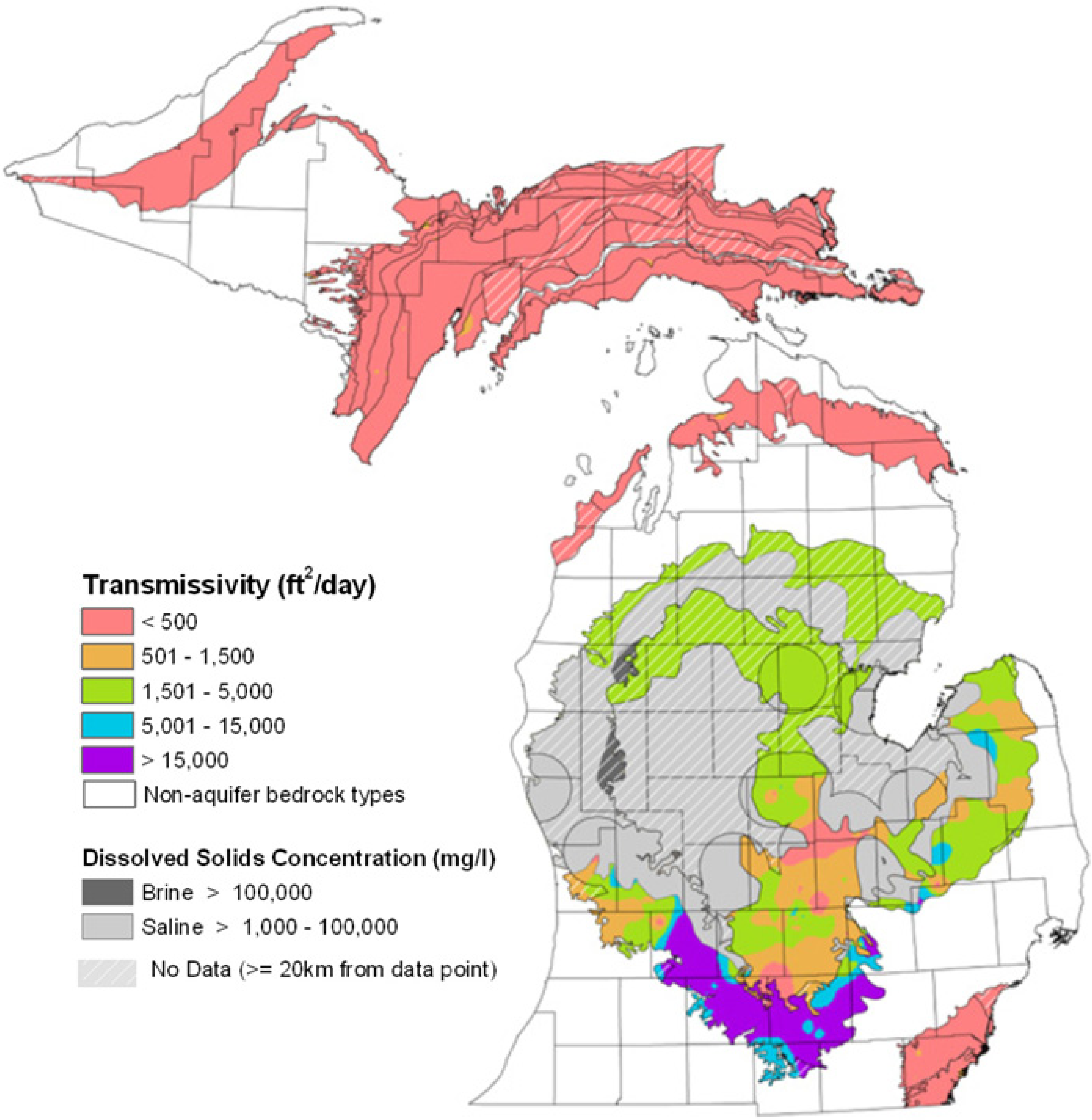

Figure 4.2.42. Estimated transmissivity for the bedrock aquifers of Michigan.

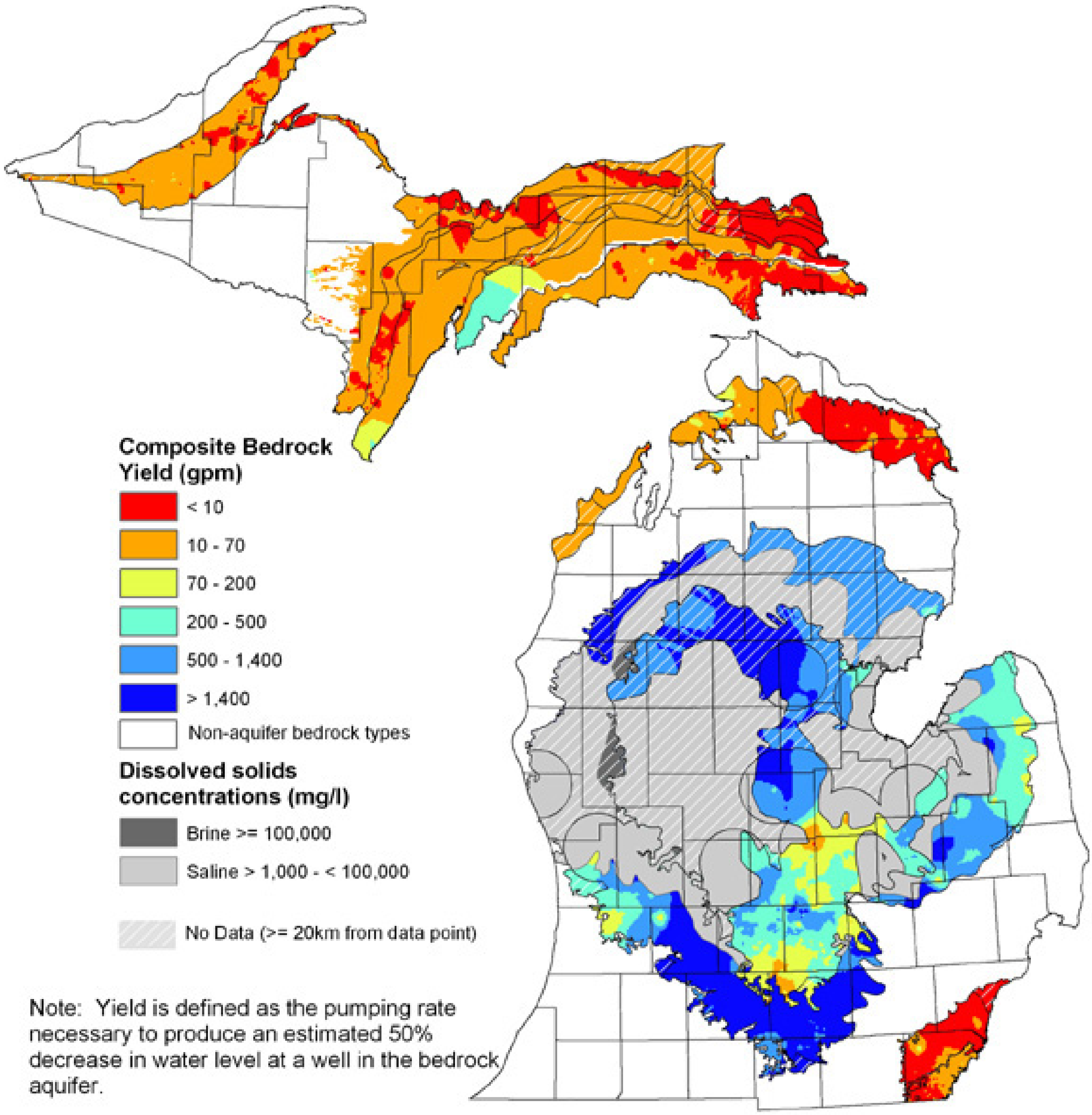

Figure 4.2.43. Estimated yield of the bedrock aquifers.

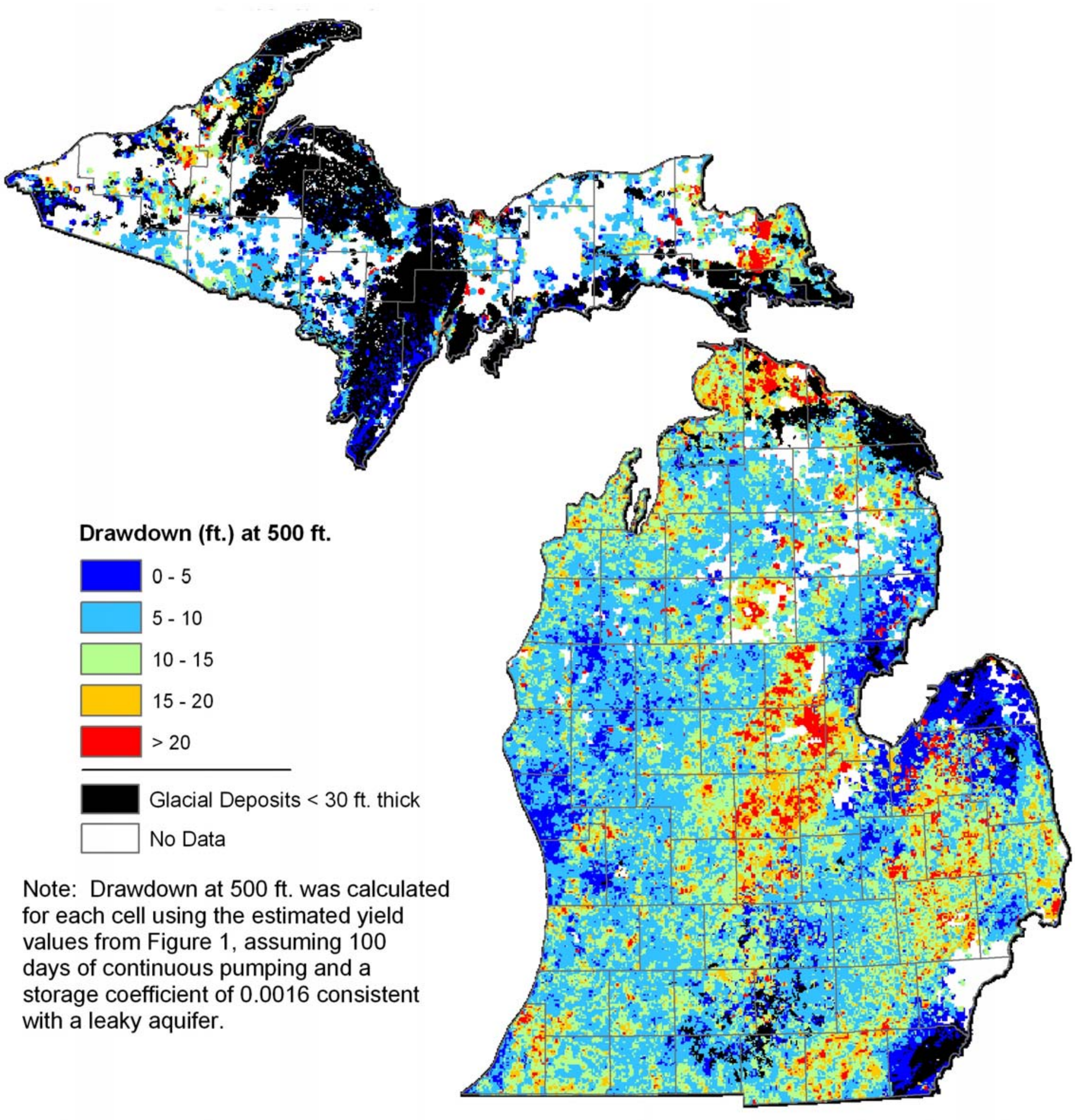

Figure 4.2.44. Drawdown estimated for the bedrock aquifers of Michigan.

4.3 (§b) Recharge

Aquifer recharge mapping in Michigan is a particularly difficult challenge for several reasons. There are many aquifers in the State, in both bedrock and glacial materials. In the best of all circumstances, individual recharge maps for each aquifer would be desirable. Unfortunately, the vertical and horizontal complexity of the glacial deposits makes glacial aquifer mapping impractical and thwarts our detailed understanding of recharge to the subjacent bedrock aquifers. From a procedural point of view, there are several methods that could be used to estimate recharge and each is appropriate for different space and time scales (Cherkauer and Ansari, 2005; Scanlon and others, 2002). The approach selected for this project is an extension of the work by Holtschlag (1996) and is based on statistical regression of baseflow estimates derived from stream-gaging records (see Section 4.5). The map by Holtschlag (1996) was not used directly, because it does not include the Upper Peninsula and because there were additional geographic data available to this project to improve the regression estimates.

Prior to providing the analysis used to derive the recharge map, a discussion of the importance of recharge is offered to prevent misuse of the map. Representative and important papers regarding recharge and the "Water Budget Myth" include Theis (1940), Bredehoeft and others (1982), Sophocleous (1997), Bredehoeft (1997), Bredehoeft (2002), and Kendy (2003). The essential message is clearly stated by Bredehoeft (1997)

"Sustainable ground-water developments have almost nothing to do with recharge; as Mario correctly states [Sophocleous, 1997], it is irrelevant. However, I continue to hear my colleagues say they are studying recharge in order to size a development – I heard this again last week. The water budget as it is usually applied to scale development is a myth..."

To appreciate this statement, the source of groundwater to wells must be recognized and the impact of pumping a well on the groundwater system must be understood.

Recharge typically refers to the amount of precipitation, either rainfall or snowmelt, that infiltrates through the ground and reaches the water table aquifer. Deeper aquifers generally are recharged with water from shallower systems. The approach used to estimate recharge is based on statistical regression of groundwater discharge (baseflow) estimates derived from stream-gaging records. The assumption is made that recharge to the shallow aquifer system is equal to baseflow. The regression technique expands on the work for the lower peninsula of Michigan by Holtschlag (1996). This method is appropriate for the shallow aquifer system (typically in the glacial deposits) that delivers most baseflow to streams and provides a long-term (1 – 80 year) average estimate of recharge for moderate areas of up to 500 square miles (Scanlon and others, 2002). Note that most bedrock aquifers in Michigan do not possess a strong hydraulic connection to the gaged streams and that the recharge map does not apply to the water delivered to bedrock aquifers from the overlying glacial deposits or through adjacent bedrock units.

The baseflow estimates discussed in Section 4.5 were used to estimate recharge as detailed below. Note that although the spatial distribution of streamflow gages in the Lower Peninsula (totaling 162) was generally adequate to represent most landscape settings, only 46 gages were available in the Upper Peninsula. There were too few Upper Peninsula gages to provide an adequate number of observations to support the incorporation of land cover and surficial geology data into the models. This is why the recharge map (Figure 4.3.1) in the Upper Peninsula is notably less detailed than in the

Lower Peninsula. This also means that the influences of surficial geology, such as the reduction in recharge and baseflow associated with the low-permeability lacustrine deposits in the eastern Upper Peninsula, as well as the effects of land cover, have been ignored in the estimation procedure undoubtedly leading to an overestimation of recharge in this part of Michigan.

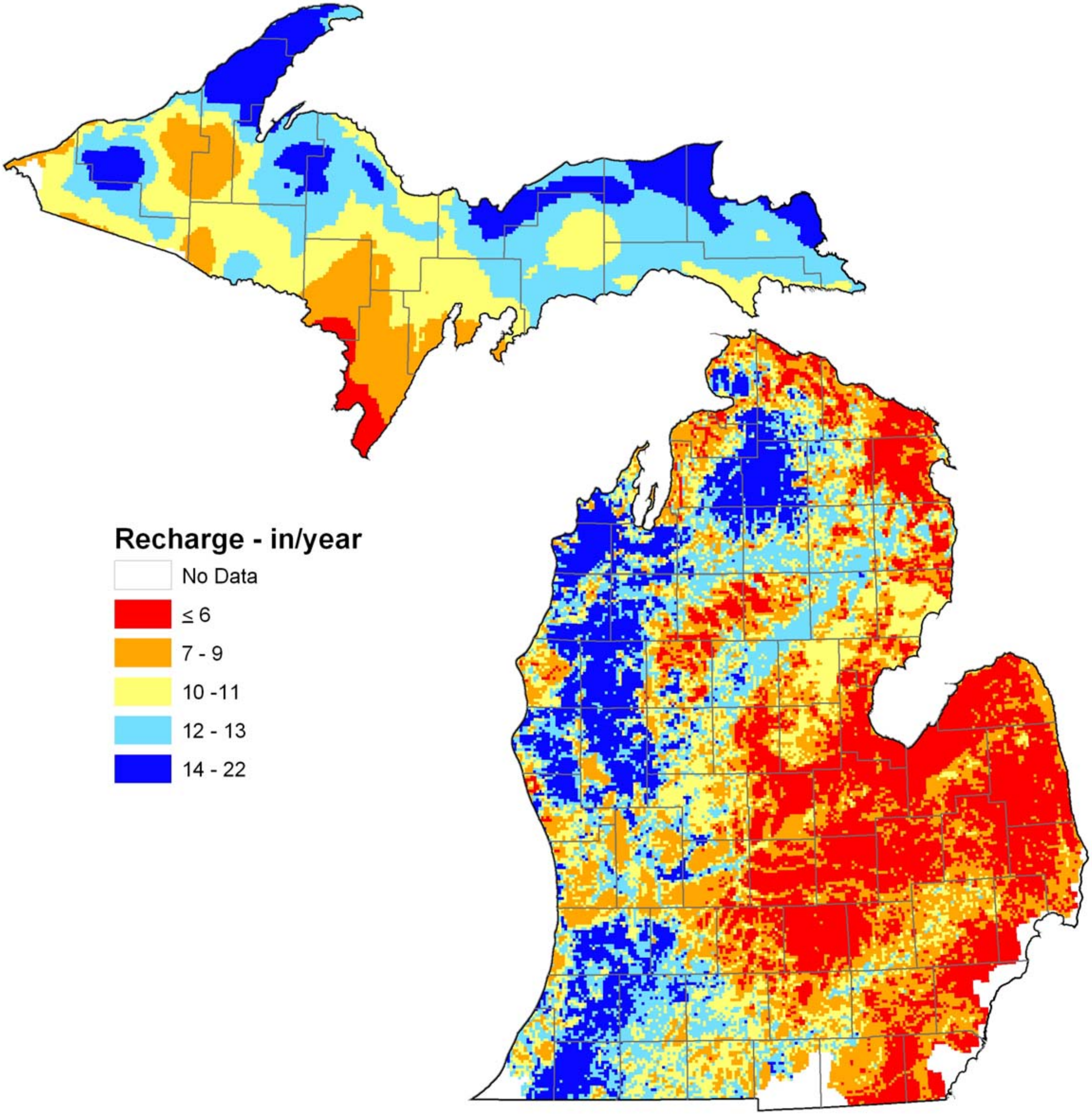

Figure 4.3.1. Estimated recharge to the shallow glacial aquifer systems.

4.4

4.4 (§c) Static Water Levels

4.4.1 Introduction

Mapping the static water levels that are recorded on the water well records in the *Wellogic* database is problematic for several reasons. First, to be done correctly, the wells must be grouped by aquifer so that wells from different confined and leaky confined aquifers are not inappropriately mixed. Only rarely, however, are detailed glacial-aquifer maps available due to the notable heterogeneity of the glacial deposits across much of Michigan. As a result, grouping wells that are screened in the glacial deposits by aquifer is almost never possible. Second, because the well records that populate the *Wellogic* database represent wells installed in various years across several decades, the static water elevations, even for wells in the same aquifer system, are often variable. Finally, note that the terminology "static water level" often is misinterpreted by the public. The static water level reported on water well records is the water level in the well after the well is developed, but prior to pumping. Groundwater levels vary naturally, both seasonally and from year to year, over a range of several feet in most places. Unfortunately, many homeowners believe that "static" water level implies that the groundwater level should be unchanging unless it is directly impacted by pumping.

About 16,000 glacial-aquifer wells in the Kalamazoo area were analyzed for temporal variations in the static water levels. These wells exhibited static water levels that varied up to six feet throughout the year, as shown on Table 4.4.1 and Figure 4.4.1. A general analysis of water levels in the Great Lakes over the past 35 years reveals notable fluctuations that can be temporally grouped into six classes: before 1970, 1970 – 1976, 1976 – 1983, 1983 – 1989, 1989 – 1998 and after 1998. Since the Great Lakes serve as the base level for groundwater discharge, fluctuations in their surface water elevation should be reflected in long-term measurements of groundwater levels, as well. The static water elevation at the time of well installation as recorded on 17,680 *Wellogic* records from Kalamazoo County were analyzed. Across these various lake-level periods, differences in average static water elevation of as much as 22 feet become apparent (Table 4.4.2 and Figure 4.4.2). Not all of these fluctuations in static water level can be attributed to climatic variation, however, since Kalamazoo County (like many areas in Michigan) has seen increased groundwater use over this same time frame.

Table 4.4.1. Static water levels, by annual quarter, reported from about 16,000 *Wellogic* records in the Kalamazoo area.

	Jan-Mar	Apr-June	July-Sept	Oct-Dec
Number of wells	2662	4559	5028	3939
Avg SWL	840	838	841	840

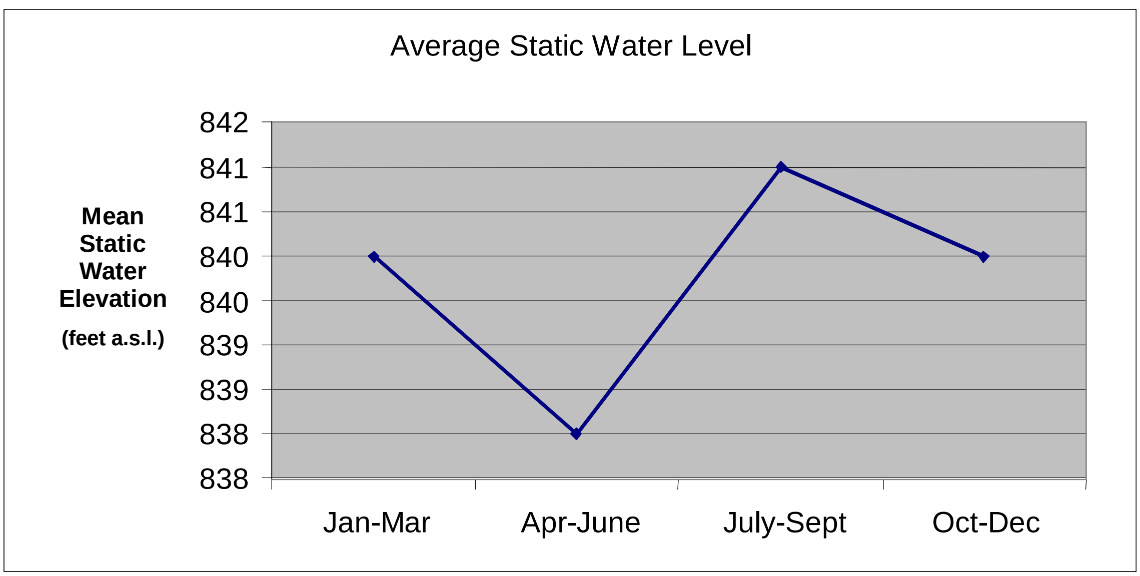

Figure 4.4.1. Static water levels, by annual quarter, reported from about 16,000 *Wellogic* records in the Kalamazoo area.

Table 4.4.2. Static water levels, by Great Lakes water-level periods, reported from 17,680 *Wellogic* records from Kalamazoo County.

	<1970	1970-1976	1976-1983	1983-1989	1989-1998	>1998	Entire Record
Number of wells	462	1135	2108	2733	5080	6162	17680
Avg SWL	837	847	850	846	852	830	844

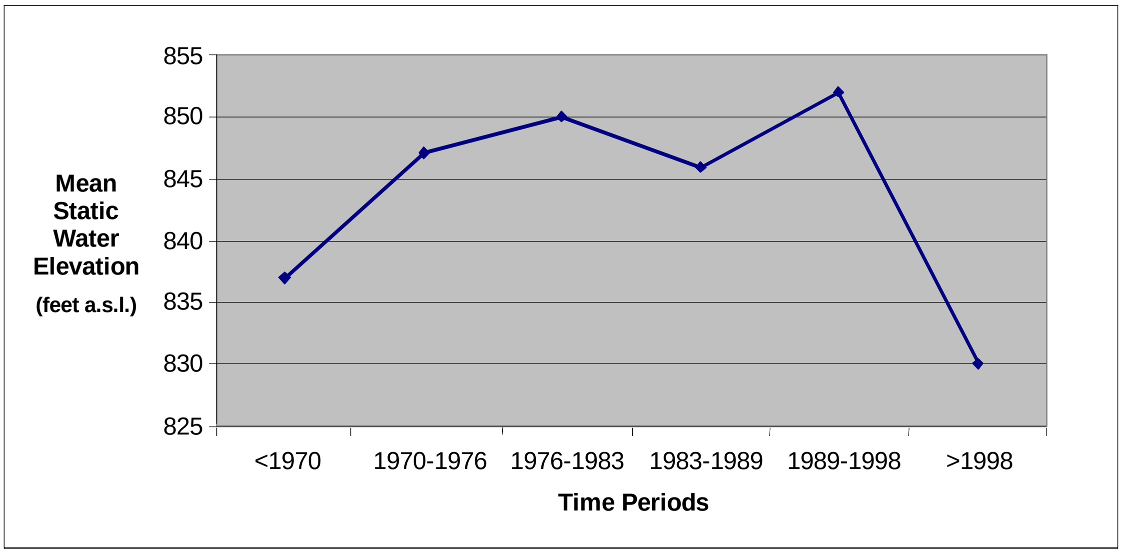

Figure 4.4.2. Static water levels, by Great Lakes water-level periods, reported from 17,680 *Wellogic* records from Kalamazoo County.

In light of these problems, this project adopted and enhanced the water table mapping protocol that had been developed for the Source Water Assessment Program (SWAP) (MDEQ, 1999). Both the old SWAP method and the enhanced protocol used several existing, digital, geospatial data sets, including:

- Michigan Framework vector base map data digitized from U.S.G.S. 7.5-minute quadrangle maps (MDIT, 2005b).

- Digital elevation data (DEM) – 7.5-minute, 30-meter postings.

(http://rockyweb.cr.usgs.gov/elevation/dpi_dem.html)

(http://www.state.mi.us/webapp/cgi/mgdl/?rel=thext&action=thmname&cid=13&cat=Digital+Elevation+Model+%28DEM%29)

- State Soil Survey (SSURGO) digital soil data.

  (http://www.dnr.state.mi.us/spatialdatalibrary/metadata/SSURGO_metadata.htm

- National Wetlands Inventory (NWI) digital data.

  (http://www.dnr.state.mi.us/spatialdatalibrary/metadata/NWI_Data.htm).

4.4.2 Surface Hydrography

Lake and ***River*** polygons (Michigan Framework version 1b), as well as the ***Rivers and Drains*** (Michigan MIRIS) vector data were obtained from the Michigan Center for Geographic Information (CGI) (<http://www.michigan.gov/cgi>). These legacy datasets (version 1b Framework and original MIRIS hydrography layers) were used instead of the current versions because inconsistent updates have been made to these layers since their creation. The lake polygon shapefile was queried to remove lakes smaller than 5 acres in size. The lake polygon shapefile for each county was visually inspected and all “lakes” that were obvious sewage treatment ponds (i.e., those with distinct rectangular shapes) were removed from the dataset. The 83 individual county datasets (Figure 4.4.3) for each of these three layers were combined into a seamless, statewide dataset.

County boundaries (Michigan framework version 3b), also obtained from CGI, were buffered by 1 mile to the outside using ArcGIS (version 8.3). These county-buffer polygons were used to clip out each “county+” area from the statewide hydrography dataset described above. The clipped hydrography shapefiles were converted into 30-

meter raster grids and subsequently reclassified to give feature cells a value of 1 and all other cells a *NoData* value.

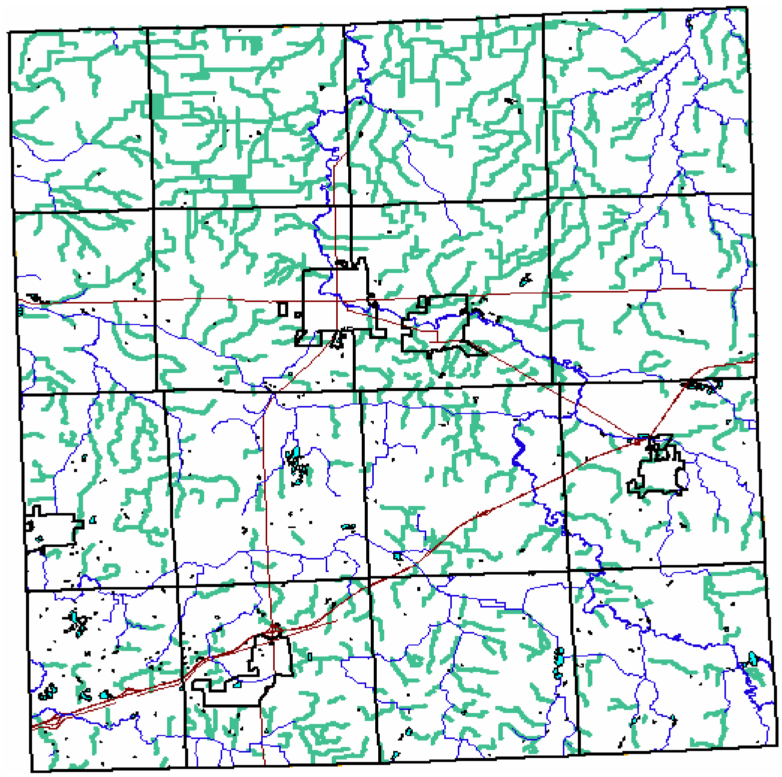

Figure 4.4.3. Hydrography in Shiawassee County from Michigan Framework Data. Thick (green) lines = intermittent features; thin (blue) lines = perennial features.

The digital elevation model (DEM) used in this study was the USGS National Elevation Dataset (NED). The NED is a seamless mosaic of best-available elevation data. The 7.5-minute elevation data for the conterminous United States are the primary initial source data. In addition to the availability of complete 7.5-minute data, efficient processing methods were developed to filter production artifacts in the existing data, convert to the NAD83 datum, edge-match, and fill slivers of missing data at quadrangle seams. One of the effects of the NED processing steps is a much-improved base of elevation data for calculating slope and hydrologic derivatives. The original version of this dataset was downloaded from the USGS EROS Data Center ftp site at <ftp://edc.usgs.gov/pub/data/ned/>. NED is also distributed on the *Seamless Data Distribution System* site (<http://seamless.usgs.gov/viewer.htm>).

The NED covering the extent of the state of Michigan was converted to integer decimeter grids and the individual geographic tiles were seamed together using the MERGE command in ArcInfo. This statewide NED mosaic was projected to Michigan GeoRef and then converted into decimal meters. A new field (***elev_feet***) was added to the database and calculated (calc *elev_feet* = grid-code * 3.28). Finally, the statewide NED mosaic was clipped into 83 county+ tiles using the Framework Version 3b county boundaries with their one-mile, exterior buffers applied (Figure 4.4.4).

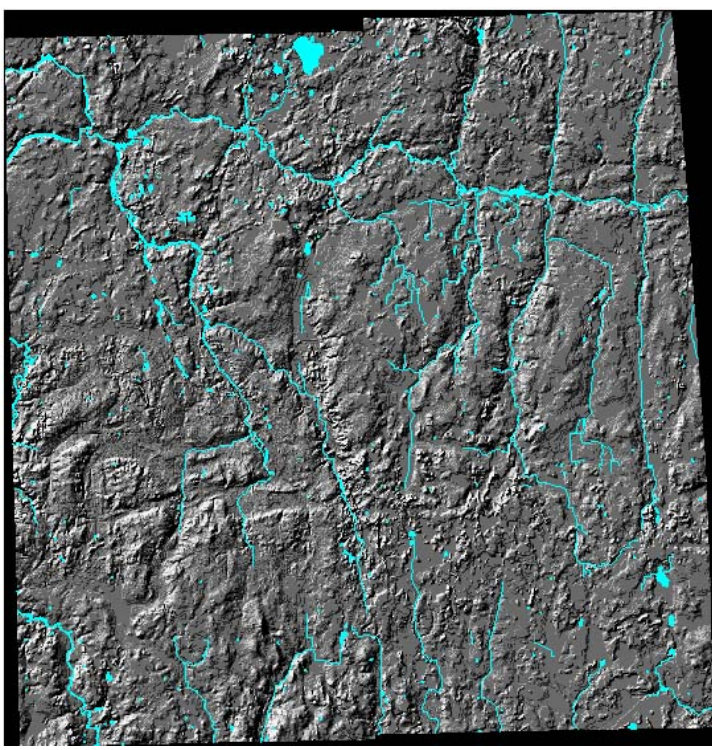

Figure 4.4.4. Hillshade presentation of the Ingham County 30-meter DEM with the perennial hydrography overlaid.

Each of the county+ hydrography grids (1,0 binary file) were multiplied times the NED elevation grid to obtain an elevation value for each feature cell. For the MIRIS drain layer, however, 2 feet were subtracted from the DEM to establish each intermittent stream cell value [grid * (DEM - 2)]. The resulting raster file was then converted to a point file whose attribute was "elevation of surface waters".

Antrim, Crawford, Kalkaska and Otsego counties have very little surface hydrography. Therefore, this area of the state was supplemented with unconfined glacial well data. The water well records for these four counties were extracted from the *Wellogic* database and queried for glacial wells that contained little or no confining material between the static water elevation and the well screen. Each of these counties is dominated by sandy glacial deposits, so in most cases the static water depth in the digital well record represents the water table. The elevation values were determined by subtracting the static water level from the surface elevation determined from the 30 meter DEM. The location of the wells in these counties is approximate (i.e., very few GPS locations) which occasionally resulted in an incorrect surface elevation being derived, resulting in an erroneous static water elevation. A draft interpolated water table surface overlaid with the well point file was visually inspected. Single wells or small isolated groupings of wells that exhibited static water levels significantly different from their neighbors (isolated peaks or pits on the draft water table surface) were removed. All of the eliminated wells were located in areas of high local relief where small horizontal misplacements could result in significantly different surface elevations.

4.4.3 Near-surface Water Table Observations

For the purpose of this project, the evidence of near-surface groundwater as recorded in the SSURGO version 2 digital soils database was determined to be the most desirable dataset. However, SSURGO version 2 soils were not available for every county at the time of processing. In the absence of SSURGO-2 data, evidence of near-surface groundwater was extracted from, in order of preference, SSURGO version 1 digital soils, MIRIS unrectified digital soils or the National Wetlands Inventory (NWI) data.

The following list indicates the primary dataset used for each county.

- **SSURGO version 1 digital soils**: Alcona, Antrim, Barry, Bay, Branch, Clinton, Crawford, Emmet, Gladwin, Hillsdale, Iosco, Marquette, Midland, Montmorency, Presque Isle, Saginaw, Tuscola.
- **SSURGO version 2 digital soils**: Alpena, Arenac, Baraga, Berrien, Charlevoix, Cheboygan, Chippewa, Genesee, Grand Traverse, Gratiot, Isabella, Kalkaska, Keweenaw, Lapeer, Leelanau, Luce, Mackinac, Macomb, Mason, Mecosta, Monroe, Montcalm, Muskegon, Newaygo, Oakland, Oceana, Ogemaw, Osceola, Oscoda, Otsego, Roscommon, Sanilac, Shiawassee, St. Clair, St. Joseph, Wayne.
- **MIRIS digital soils**: Ingham, Jackson, Kent, Lenawee, Livingston, Washtenaw.
- **National Wetland Inventory data**: Alger, Allegan, Benzie, Calhoun, Cass, Clare, Delta, Dickinson, Eaton, Gogebic, Houghton, Huron, Ionia, Iron, Kalamazoo, Lake, Manistee, Menominee, Missaukee, Ontonagon, Ottawa, Schoolcraft, Van Buren, Wexford.

4.4.3.1 SSURGO Version 1 Soils

SSURGO version 1 digital soils for the 17 counties listed above were downloaded from either the NRCS SSURGO database or from the NRCS soil data mart

(<http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/>) or (<http://soildatamart.nrcs.usda.gov/>). All 17 SSURGO-1 county soils datasets were merged into one statewide file. All soil polygons containing an "apparent" water table type (in the SSURGO database the actual water table is referred to as "apparent" in contrast to a "perched" water table) and larger than 1 acre in size were selected. The resulting statewide query file was clipped using each county's 1- mile buffer shapefile. A 90-meter grid was created for each of the 17 counties (*shapegrid* command in ArcInfo workstation), with the grid value set to the seasonally low water table depth in the shapefile. The resulting grid was then subtracted from the NED DEM to establish the elevation of the water table. Lastly, a point file was created from this 90-meter grid (*gridpoint* command in ArcInfo workstation).

4.4.3.2 SSURGO-version 2 Soils

SSURGO version 2 digital soils data for the 36 counties listed above were downloaded from either the NRCS SSURGO database or from the NRCS soil data mart (<http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/> or <http://soildatamart.nrcs.usda.gov/>). SSURGO-version 2 has a completely different database structure than the version 1 counterpart. The MS Access table for each SSURGO-2 dataset was queried for wet soils (i.e., water table in the solum – a depth of 6 to 7 feet, depending on when the survey was done) and there was water in the root zone for at least one month (see Appendix 8.1). Only map units of 1 acre or more in size were used. The resulting statewide query file was clipped using each county's 1- mile buffer shapefile. A 90-meter grid was created for each of the 36 counties (*shapegrid* command in ArcInfo workstation), with the grid value set to the seasonally deepest water table depth in the shapefile. The resulting grid was then subtracted from the NED DEM to establish the elevation of the water table. Lastly, a point file was created from this 90-meter grid (*gridpoint* command in ArcInfo workstation).

4.4.3.3 Michigan MIRIS Soils (unrectified digital soils)

The MIRIS (Michigan Resource Information System) soils dataset for six counties were obtained from the Michigan Center for Geographic Information (<http://www.michigan.gov/cgi>). MIRIS soils were digitized directly from the published county soil surveys (none of which used orthoimagery) and registered to the public land survey section layer in Framework - version 1. All six MIRIS soils shapefiles were merged into a single statewide shapefile. Soil polygons greater than or equal to 1 acre were extracted and saved as a new shapefile. The resulting statewide query file was clipped using each county's 1- mile buffer shapefile. A 90-meter grid was created for each of the 6 counties (*shapegrid* command in ArcInfo workstation), with the grid value set to the seasonally deepest water table depth in the shapefile. The resulting grid was then subtracted from the NED DEM to establish the elevation of the water table. Lastly, a point file was created from this 90-meter grid (*gridpoint* command in ArcInfo workstation) (Figure 4.4.5).

A master soils point file was created that contained the SSURGO-1, SSURGO-2 and MIRIS soils data. This master soil file was clipped using each county's 1-mile buffer shapefile.

4.4.3.4 National Wetlands Inventory

For the 24 counties listed above where SSURGO or MIRIS soil data were unavailable, the National Wetland Inventory (NWI) data were used (http://www.nwi.fws.gov). For more details on the NWI coding structure, see the NWI mapcode download site: (ftp://www.nwi.fws.gov/maps/mapcode.txt). NWI data were downloaded from the Michigan Center for Geographic Information (<http://www.michigan.gov/cgi>) and merged into one statewide file. By query, all NWI

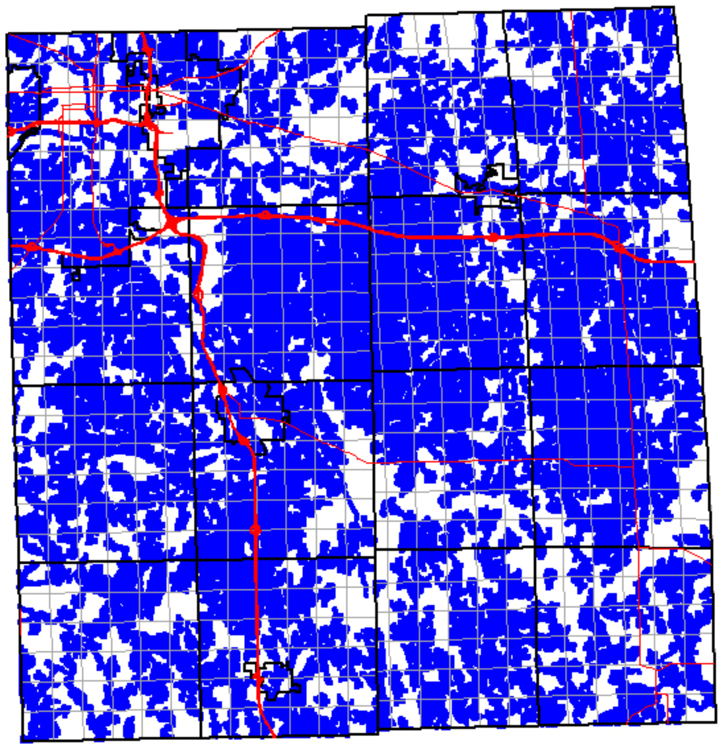

Figure 4.4.5. Points (90-meter spacing) extracted from MIRIS soils data recording the depth to the water table (SSURGO-1 and -2 looked similar).

polygons at least 1 acre in size where the wetland system was noted as "Palustrine" were extracted. For each county, a 90-meter grid was created (*shapegrid* command in ArcInfo workstation) and reclassified setting all wetlands cells to a value of 1 and all other cells to a value of *NoDATA*. This wetlands grid was multiplied times the DEM minus 1 foot to calculate an estimated water table elevation for each cell. This constant (-1 ft) was determined by a test that overlaid all the NWI palustrine polygons onto the SSURGO-1 soils data in four selected counties (Antrim, Ingham, Kent and Monroe). The percentage of the coincident areas (i.e., palustrine wetland *and* SSURGO map unit where the water table type was coded as "apparent"), is shown in Table 4.4.2. Finally, a point file was created from the 90-meter wetlands water table grid using the *gridpoint* command in ArcInfo workstation (Figure 4.4.6).

Table 4.4.2. Percentage of areas coincident between NWI palustrine wetlands and SSURGO-1 map units where the field ***wtkind*** = apparent, by water table depth. Note that in all four counties, the dominant water table depth associated with NWI palustrine wetlands is 1 foot or less.

wtdeph value	**Antrim County**	**Ingham County**	**Kent County**	**Monroe County**
0 ft.	9.05 %	-	9.03%	58.37%
1 ft.	71.35%	68.97%	63.68%	13.86%
2 ft.	10.61%	17.27%	24.99%	17.22%
3 ft.	2.37%	8.54%	1.14%	4.58%
5 ft.	-	-	1.16%	-
6 ft.	6.62%	5.22%	-	5.97%

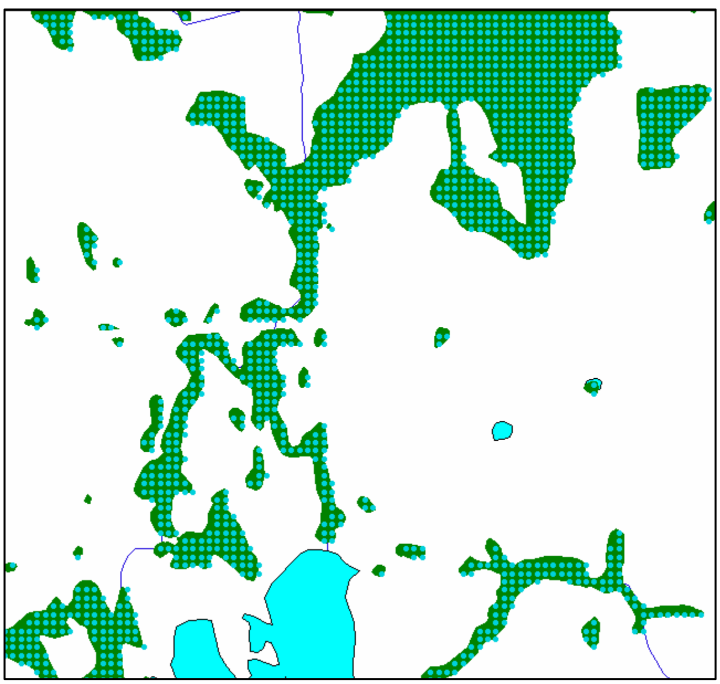

Figure 4.4.6. Points (90-meter spacing) extracted from the palustrine polygons in the National Wetlands Inventory data (2 sq. mile area from Bennington Twp., Shiawassee County).

Unconfined drift wells were extracted from the MDEQ *Wellogic* database for Antrim, Crawford, Kalkaska and Otsego counties because these counties have very few surface water features and are underlain by generally well drained soils (i.e., no soils-derived nor wetland-derived water table data). Since there were relatively few "water table elevation" points in this area, the block of four contiguous counties was supplemented with unconfined drift well data.

The *Wellogic* database was queried for wells in Antrim, Crawford, Kalkaska or Otsego counties that contained little or no confining material in the saturated thickness between the static water level and the bottom of the well screen (***A_HIT_SWL* = T** *and* ***A_PCT_AQ* >= 80**). In truly unconfined wells, the static water level represents the depth of the water table. Water table elevation values were determined by subtracting the static water level from the surface elevation, as given by the 30-meter DEM. The location of the wells in many areas is only approximate which occasionally results in an incorrect water table elevation being derived. Therefore, the initial water table surface interpolated from these wells was visually inspected for localized peaks and pits. Wells exhibiting significantly different static water levels compared to nearby features were removed, especially if they were located in areas of high topographic relief (the dominant case).

4.4.3.5 Great Lakes and Connecting Channels (Base level for the water table)

The Great Lakes shoreline shapefiles were downloaded from the Michigan Center for Geographic Information (<http://www.michigan.gov/cgi>) and merged into one statewide file. This line file was buffered by 90 meters and the resulting polygon file was rasterized to a 30-meter grid using the *shapegrid* command in ArcInfo workstation. From this grid file, a point coverage was made using the *gridpoint* command in ArcInfo workstation. Using this point coverage, all points that fell on the Great Lakes side of the county boundary were selected and exported to a "near-shore" shapefile. Various groupings of near-shore points were selected from this file and their elevation values were established based on the mean annual lake levels for the period from 1918 to 2002 [elevations in feet, referenced to the International Great Lakes Datum of 1985 (IGLD 85)] as determined by the US Army Corps of Engineers (2005).

The points for all counties along Lake Superior, except Chippewa, were set to an elevation of 602 feet. For Chippewa County, the points throughout Whitefish Bay were set to 602 ft also, but beginning at the head of the St. Marys River at Brush Point and downstream to the northeast corner of Sugar Island, the points were set as shown in Figure 4.4.7. From Sugar Island downstream to the south end of Neebish Island, the point elevations were assigned as shown in Figure 4.4.8. All points in Munuscong Lake as far south as Point aux Frenes were set to 580 feet. Below Point aux Frenes, all points were set to 579 feet (Figure 4.4.9).

The points for all Lake Michigan counties, without exception, were set at 579 feet. The points for Lake Huron counties from Cheboygan County southward to, and including, Sanilac County were also set to 579 feet, as were the points for St. Clair County southward to the mouth of Lake Huron. Beginning at the head of the St. Clair River the points were assigned values as shown in Figure 4.4.10.

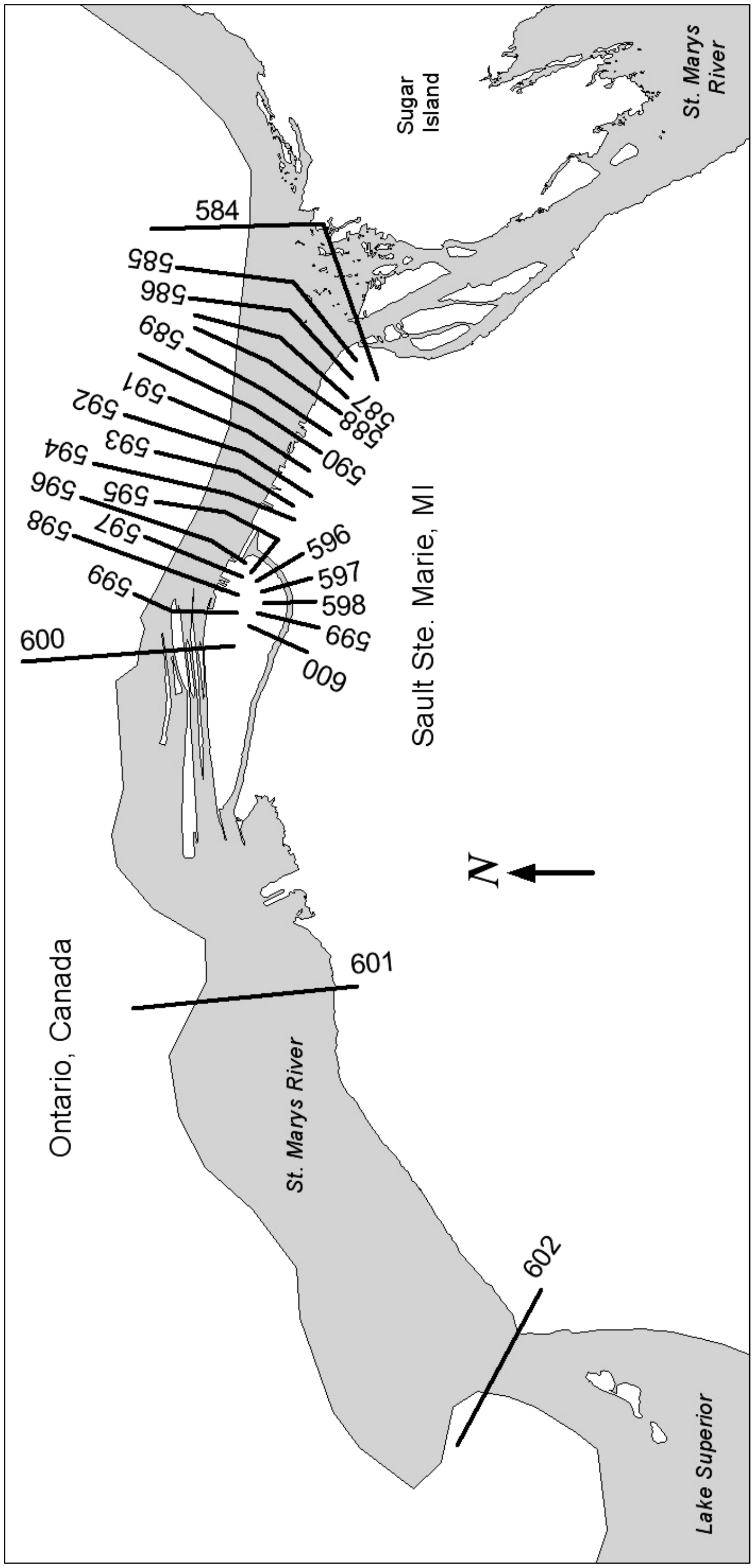

Figure 4.4.7. Elevations (feet, IGLD 85) along the Upper St. Marys River.

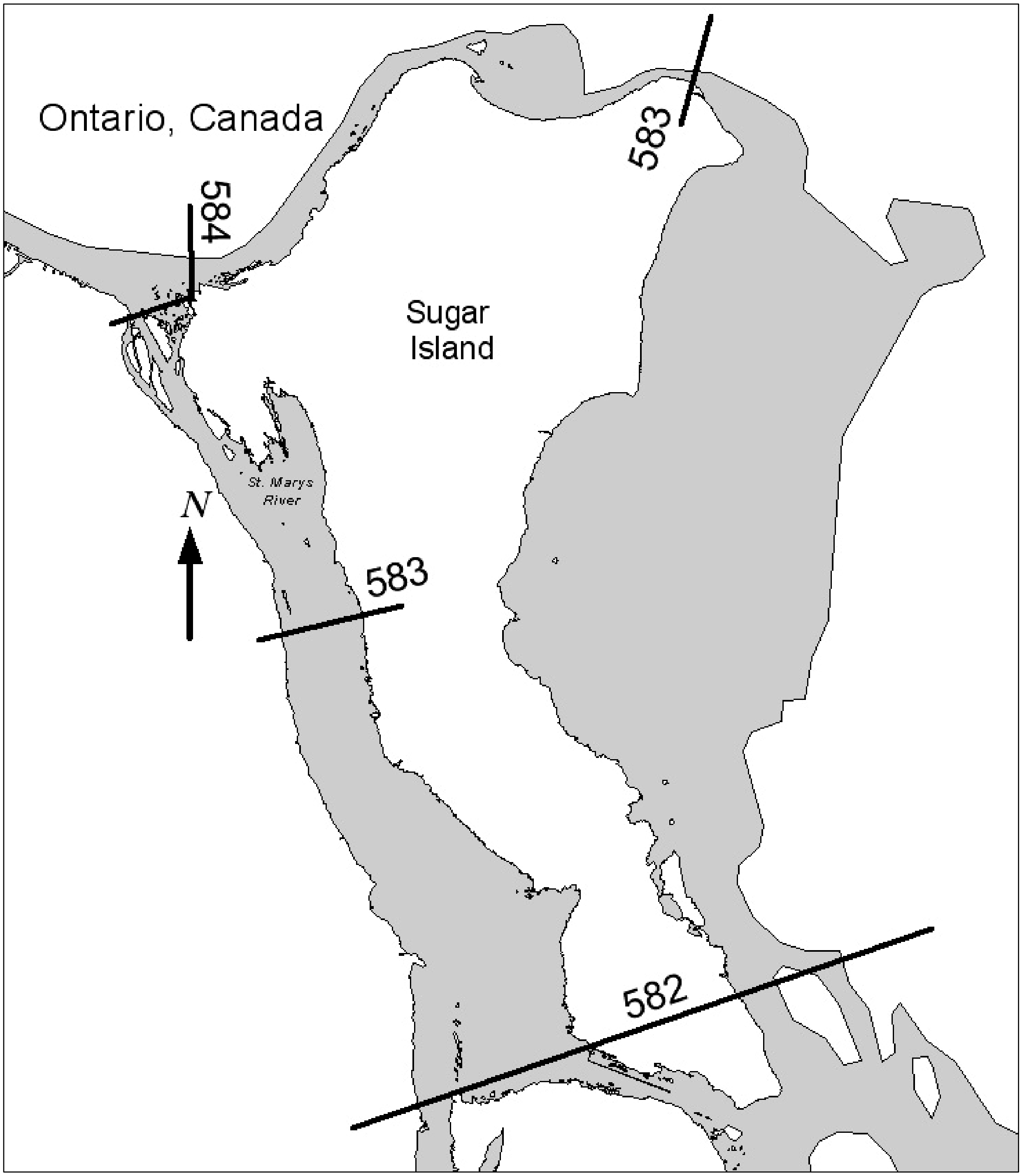

Figure 4.4.8. Elevations (feet, IGLD 85) along the Middle St. Marys River.

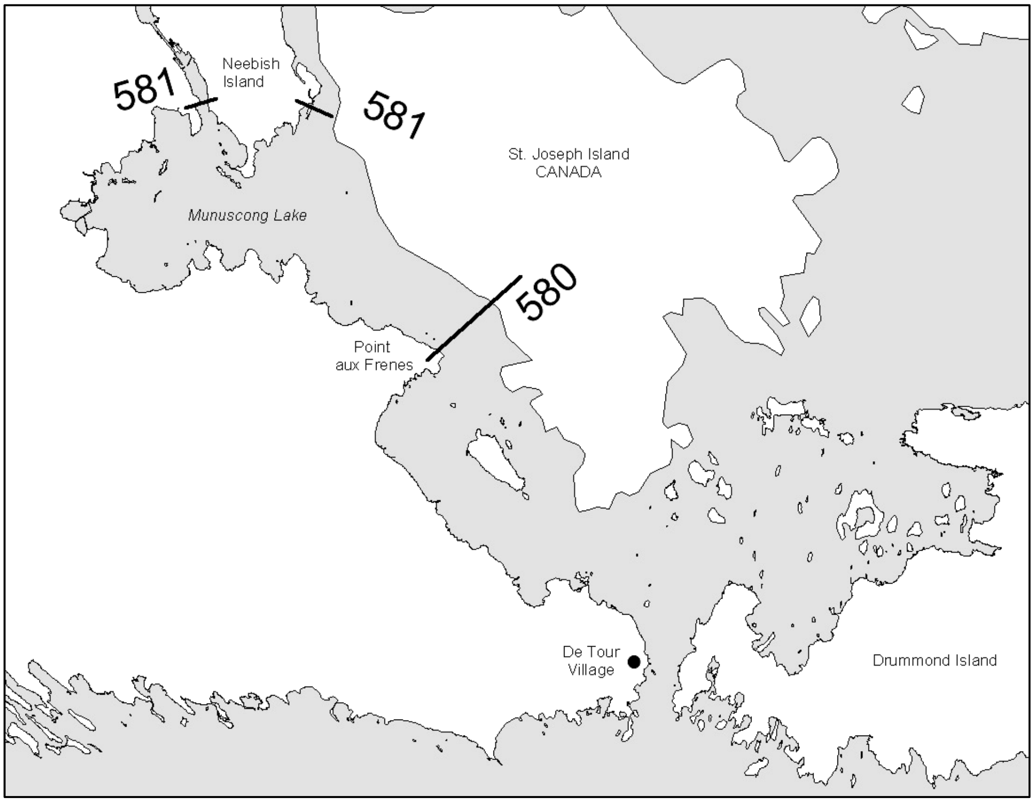

Figure 4.4.9. Elevations (feet, IGLD 85) in the vicinity of Munuscong Lake.

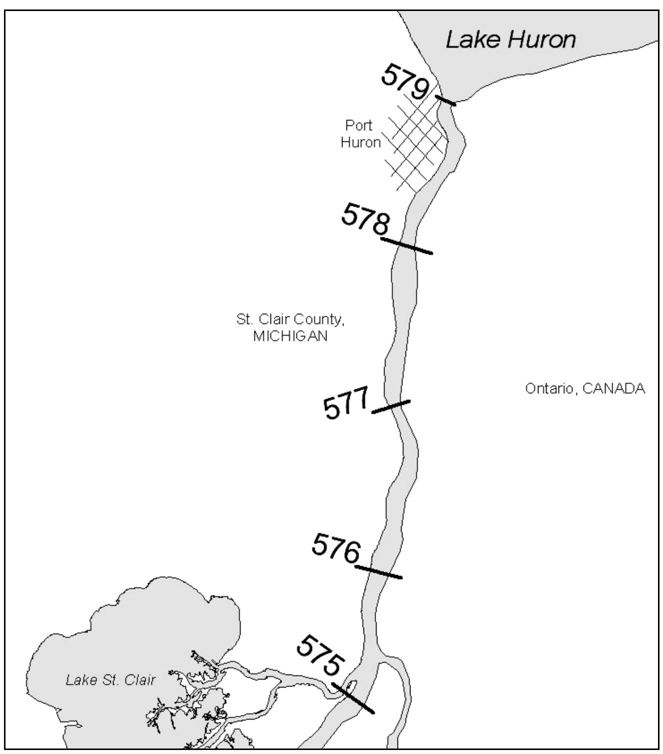

Figure 4.4.10. Elevations (feet, IGLD 85) along the St. Clair River.

All the points for Lake St. Clair adjacent to Macomb County were set to an elevation of 574 feet, as were the points adjacent to Wayne County from the Macomb-county line south to the head of the Detroit River. Beginning at the head of the Detroit River (at Windmill Point– Peach Island), the elevations for the Detroit River are shown on Figure 4.4.11. All the points for Lake Erie were set to an elevation of 571 feet.

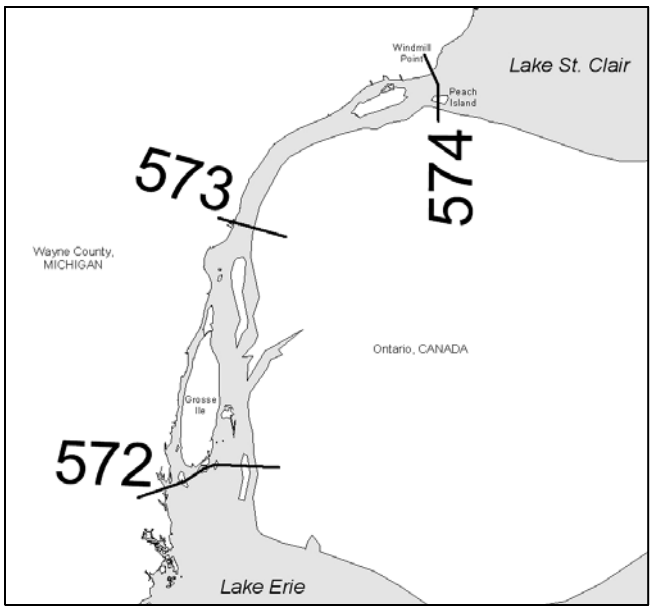

Figure 4.4.11. Elevations (feet, IGLD 85) along the Detroit River.

4.4.3.6 Merged Point File Creation and Water Table Interpolation.

For each county, a merged point file was created from the combination of hydrography elevation points and the soils or NWI data points using the ***append*** command in ArcInfo workstation . Where appropriate, this merged point shapefile was merged again with the Great Lakes elevation points and/or the static water elevation points from the unconfined wells in Antrim, Crawford, Kalkaska or Otsego counties (Figure 4.4.12).

Using the ArcGIS ***Geostatistical Analyst***, the water-table elevation surface was interpolated for a regular grid of 30-meter cells using all the spatially irregular points mentioned above (merged point file). The following parameters were set:

- Interpolation Attribute — Elevation
- Method — Kriging, ordinary
- Handling of Coincident Samples — Use Maximum
- Transformation — None
- Order of Trend Removal — None
- Semi-variogram Model — Spherical
- Lag Size — 300 (horizontal coordinates are in meters)
- Number of Lags — 12
- Search Direction — None
- Searching Method — Neighborhood
- Neighbors to include — 12
- Minimum Neighbors to Include — 6
- Shape Type — 4 sectors with 45 degree offset
- Cell Size of Output — 30 meters

Using the ArcGIS ***Spatial Analyst***, the output grid from the Kriging process (i.e., the interpolated water table surface) was clipped using the 90-meter county-boundary buffer shapefiles. The output resolution was set to 30 meters (Figure 4.4.13).

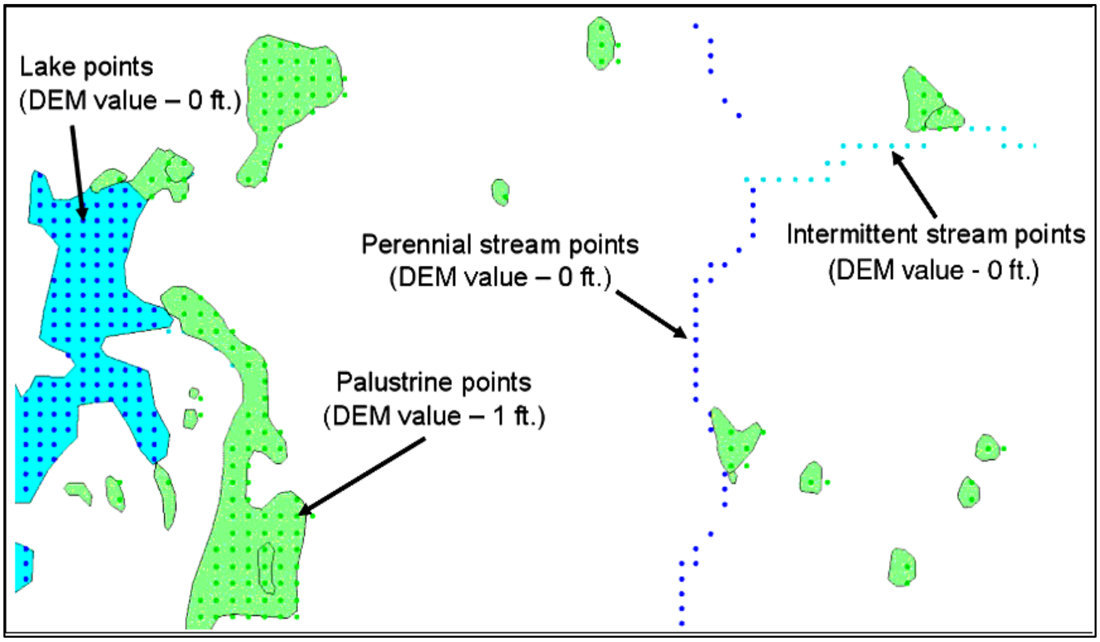

Figure 4.4.12. Merged file of water-table points from surface hydrography and NWI data.

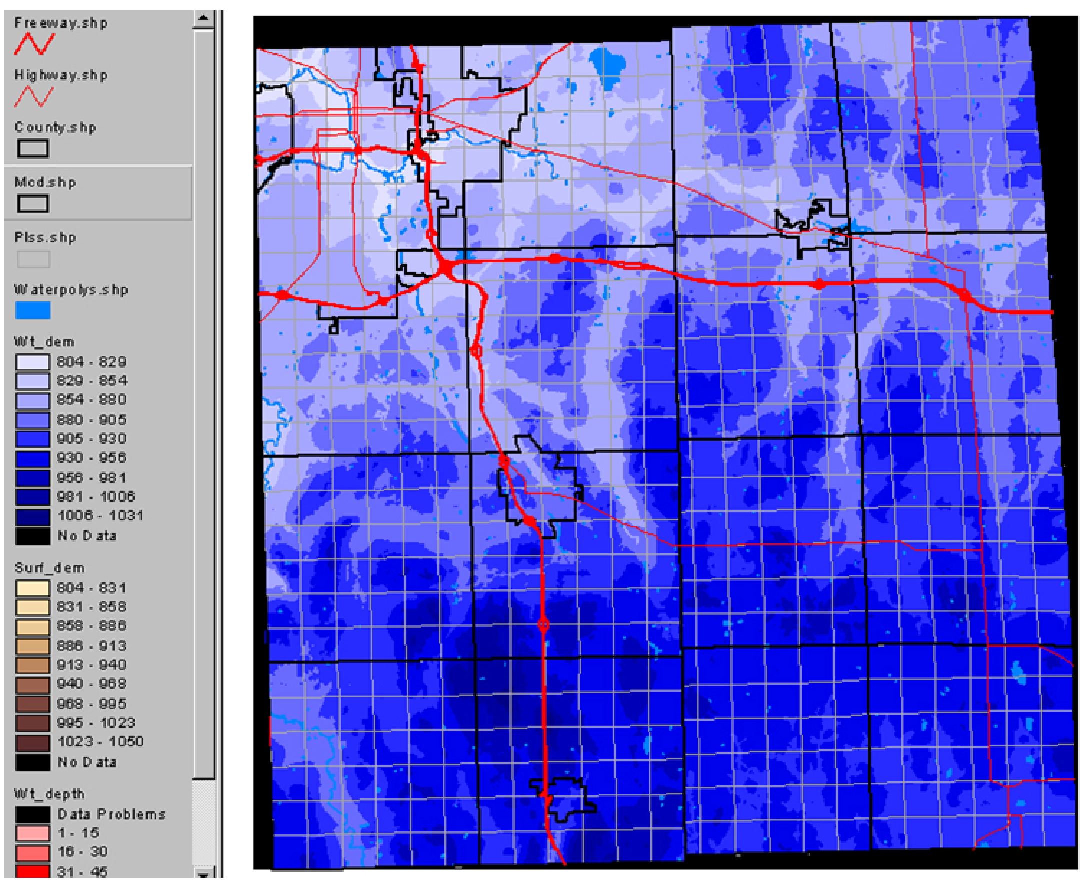

Figure 4.4.13. Interpolated water table surface (30-meter grid).

4.4.3.7 Depth to the Water Table

The 30-meter, water-table surface grid was subtracted from the 30-meter NED DEM to calculate the depth below the surface to the water table (Figure 4.4.14).

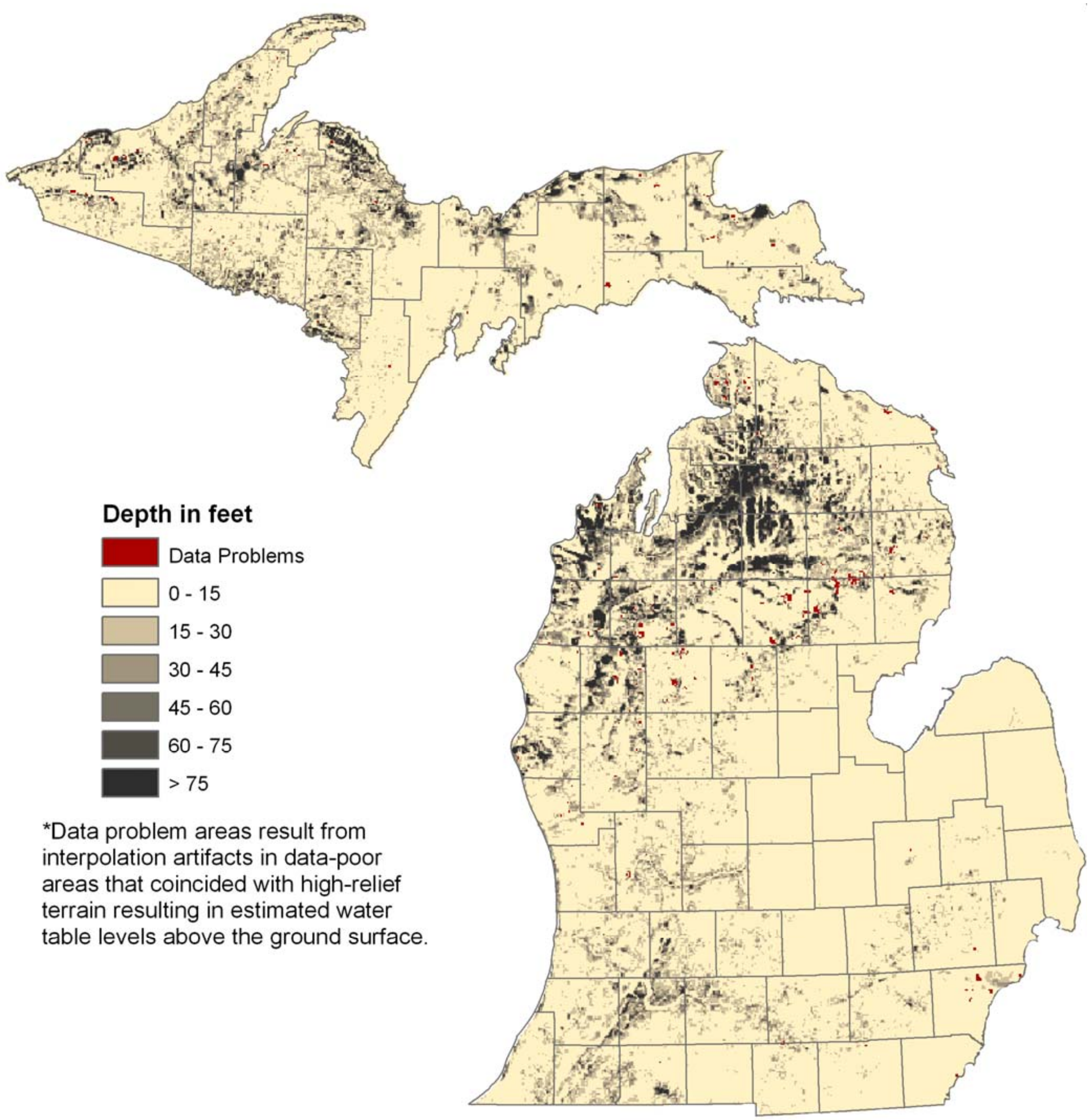

Figure 4.4.14. Interpolated depth to the water table, classed in 15-foot ranges.

4.4.3.8 Isoline Presentation of Water Table Surface.

A secondary water-table surface using a 90-meter grid spacing was interpolated using the same Kriging procedures as listed above. These raster data were converted into isoline contours (using a 10 ft. contour interval), in order to better portray the gradient and direction of flow on the water table surface (Figure 4.4.15). The contours generated from the 90-meter water-table surface are smoother with fewer irregularities in comparison to those that can be generated from the original 30-meter water-table surface.

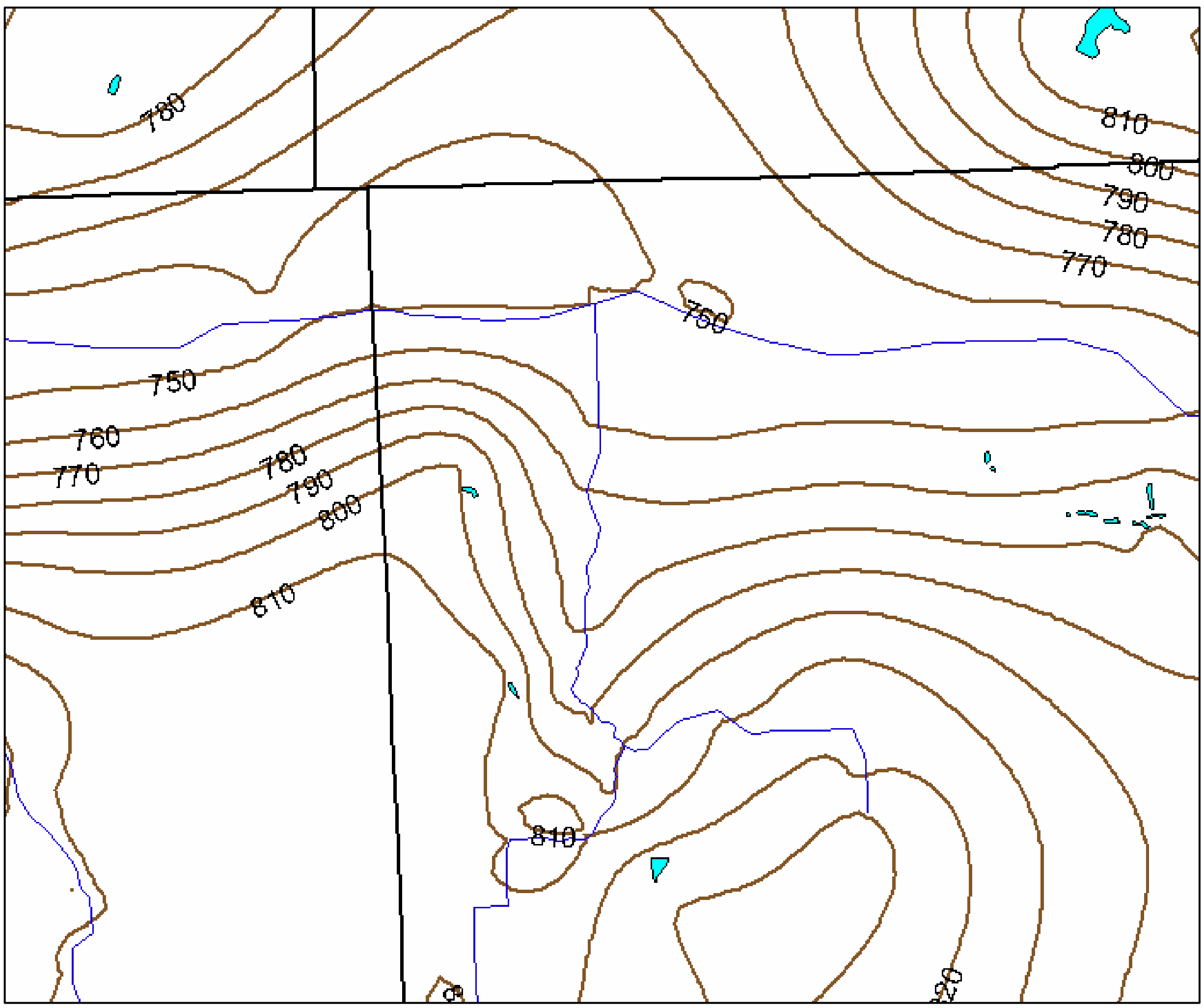

Figure 4.4.15. Isoline presentation of the interpolated water table surface (10 ft contours).

4.5(§d) Baseflow of Rivers in the State

The baseflow of a stream or river is the amount of groundwater discharged from an aquifer to the watercourse. This discharge occurs year-round, and fluctuates seasonally depending on the level of the water in the aquifer. Over the course of a year, assuming no change in the quantity of water stored in the aquifer, the total baseflow is assumed to equal the total groundwater recharge for a watershed. Baseflow is supplemented by direct runoff during and immediately after precipitation or melt events, resulting in peaks on a hydrograph showing stream flow through time. The process of dividing these peaks into base flow and runoff is called hydrograph separation.

Hydrograph separations were completed for all USGS stream flow-gaging stations in Michigan that had more than 10 years of daily records. Sites that were clearly affected by upstream impoundments (lakes, dams) were excluded. No attempt was made to detect or correct for trends in the data. This may lead to some errors in the comparison of streams with data from different time periods if there is an underlying temporal trend in the data, but inclusion of all records in the analysis was necessary to increase the data pool and provide better spatial coverage.

Watersheds were delineated for each of the 208 stream flow-gaging stations, and various characteristics of each watershed, such as topographic relief, surficial geology, land cover, growing degree days, annual and winter-season precipitation, and others were tabulated. Regression modeling, described below, was used to estimate the baseflow for each stream segment of the 1:100,000-scale National Hydrography Dataset as shown in Figure 4.5.1.

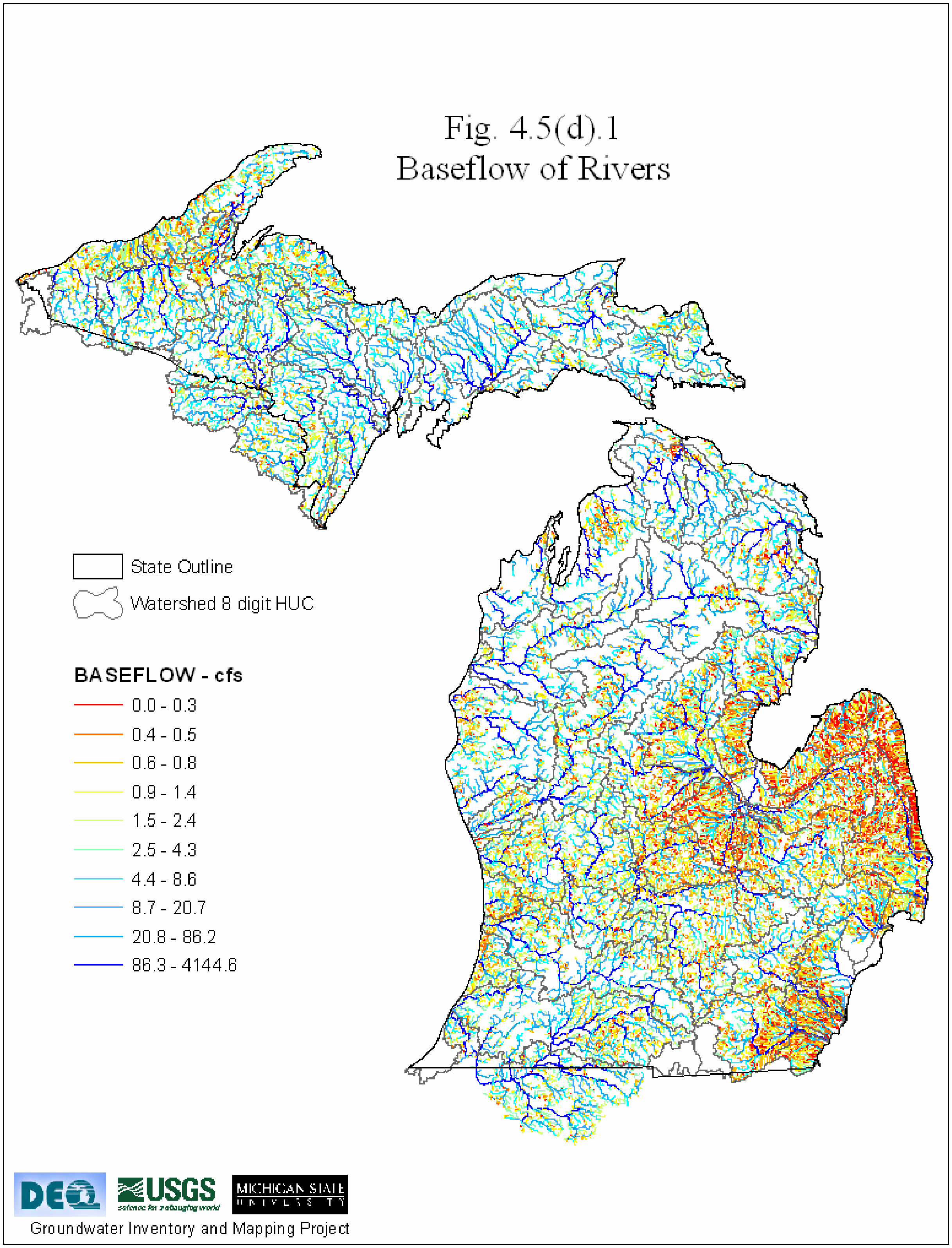

Figure 4.5.1. Estimated baseflow (cubic feet per second) of river segments.

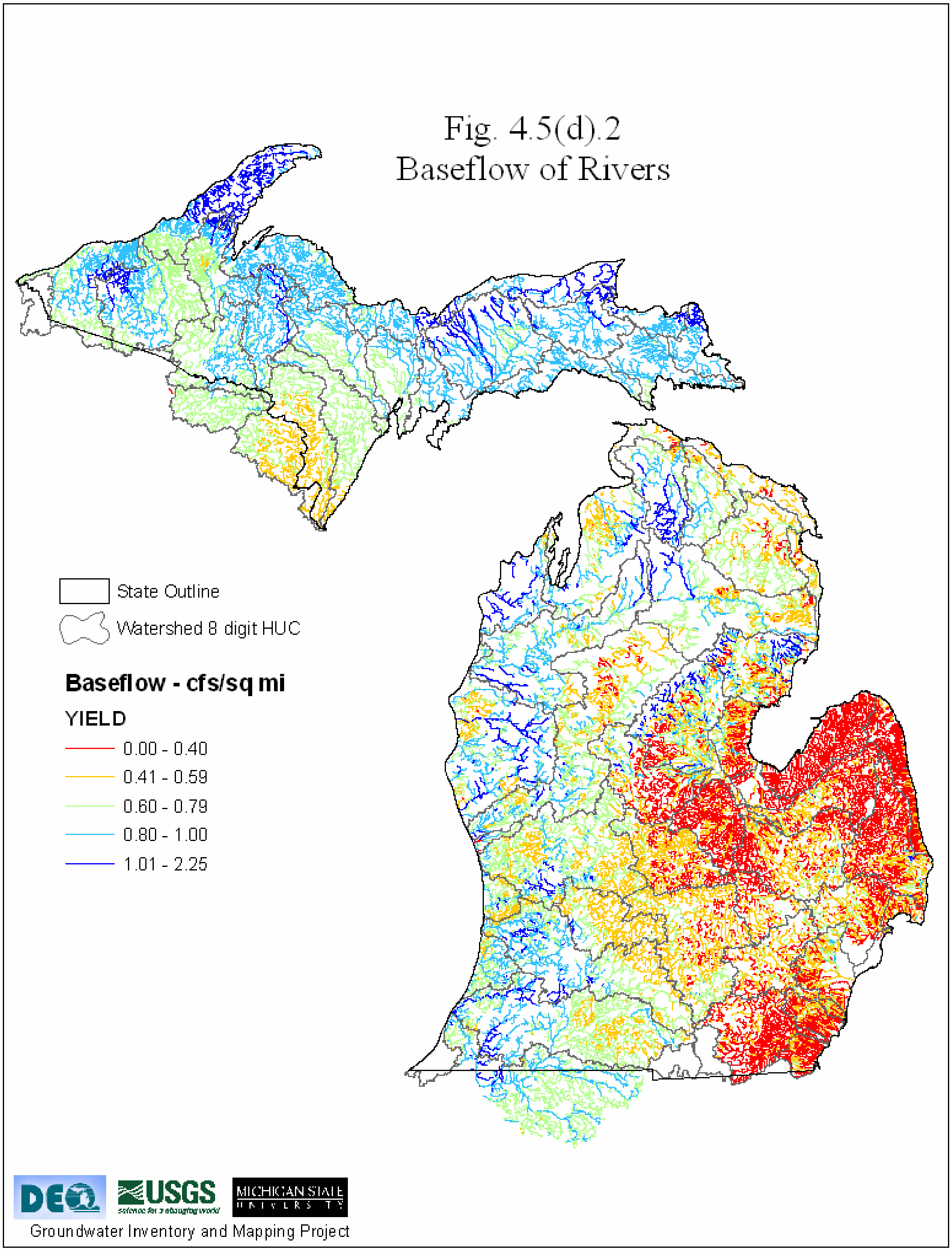

Figure 4.5.2. Estimated baseflow yield (cfs/sq. mile) of river segments.

4.6 (§e) Conflict Areas in the State

Public Act 148 (Acts of 2003) required that groundwater conflicts designated by the MDEQ under P.A. 177 (Acts of 2003) be mapped and made available to the public. P.A. 177 amended Act 451 of 1994 by adding Part 317 Aquifer Protection and Dispute Resolution.

The Groundwater Dispute Resolution Program within the Water Bureau of MDEQ investigates and resolves disputes arising from the adverse impacts of high capacity water wells on small quantity users. If a small quantity well (defined as a pumping capacity less than 70 gallons per minute [gpm]) fails to produce its normal supply of water or fails to produce potable water and the owner has credible reason to believe the well problem was caused by a high capacity well (70 gpm or more), they can file a complaint with the MDEQ. An assessment of the small quantity water well by a Michigan registered water well drilling contractor is required to rule out mechanical problems as the cause of the well failure.

The DEQ will investigate the complaint to determine if the problem is caused by the lowering of groundwater by a high capacity well; then make a diligent effort to resolve the dispute. If the suspected high capacity well is an agricultural well, the complaint is referred to the Michigan Department of Agriculture, Environmental Stewardship Division, for investigation. MDEQ staff may meet with the parties to discuss equitable solutions. Resolution of a groundwater dispute typically involves restoration or replacement of the small quantity water well or connection to a municipal water system, with the high capacity well owner reimbursing the complainant for costs incurred.

The Groundwater Dispute Resolution Program has been in operation for more than two years. DEQ began receiving complaints in October, 2003 from the two geographic areas of greatest risk (see Table 4.6.1) and from the rest of the state beginning July 1, 2004. The following information was extracted from the MDEQ web site in December, 2005.

Table 4.6.1 Groundwater dispute complaints received by MDEQ

GROUNDWATER DISPUTE COMPLAINTS

(10/1/2003 - 11/3/2005)

Resolved Complaints	25
Closed or Invalid Complaints	22
Unresolved Complaints (Antrim 1, Monroe 7, Saginaw 4)	12
Total Number of Complaints Received	59

RESOLVED COMPLAINT DETAILS

County	High Capacity Well Type	Number of Complaints
Charlevoix	Quarry Dewatering	5
Monroe	Quarry Dewatering	12
Saginaw	Agricultural	8

A total of 17 complaints involving agricultural high-capacity wells were forwarded to the Michigan Department of Agriculture for investigation. To date (November 3, 2005), 47 of the 59 complaints that had been received were either resolved or closed. Because circumstances have not required them, the MDEQ Director has not had to issue any groundwater conflict orders yet. Figure 4.6.1 shows point data related to pending or completed resolutions under Part 317 as of July 2005. As required by Section

31712 of PA 177, the MDEQ Director identified two geographic areas in the state that were at greatest risk for potential groundwater disputes. The northwesternmost four townships in Saginaw County and all of Monroe County were designated as conflict areas and are also shown in Figure 4.6.1.

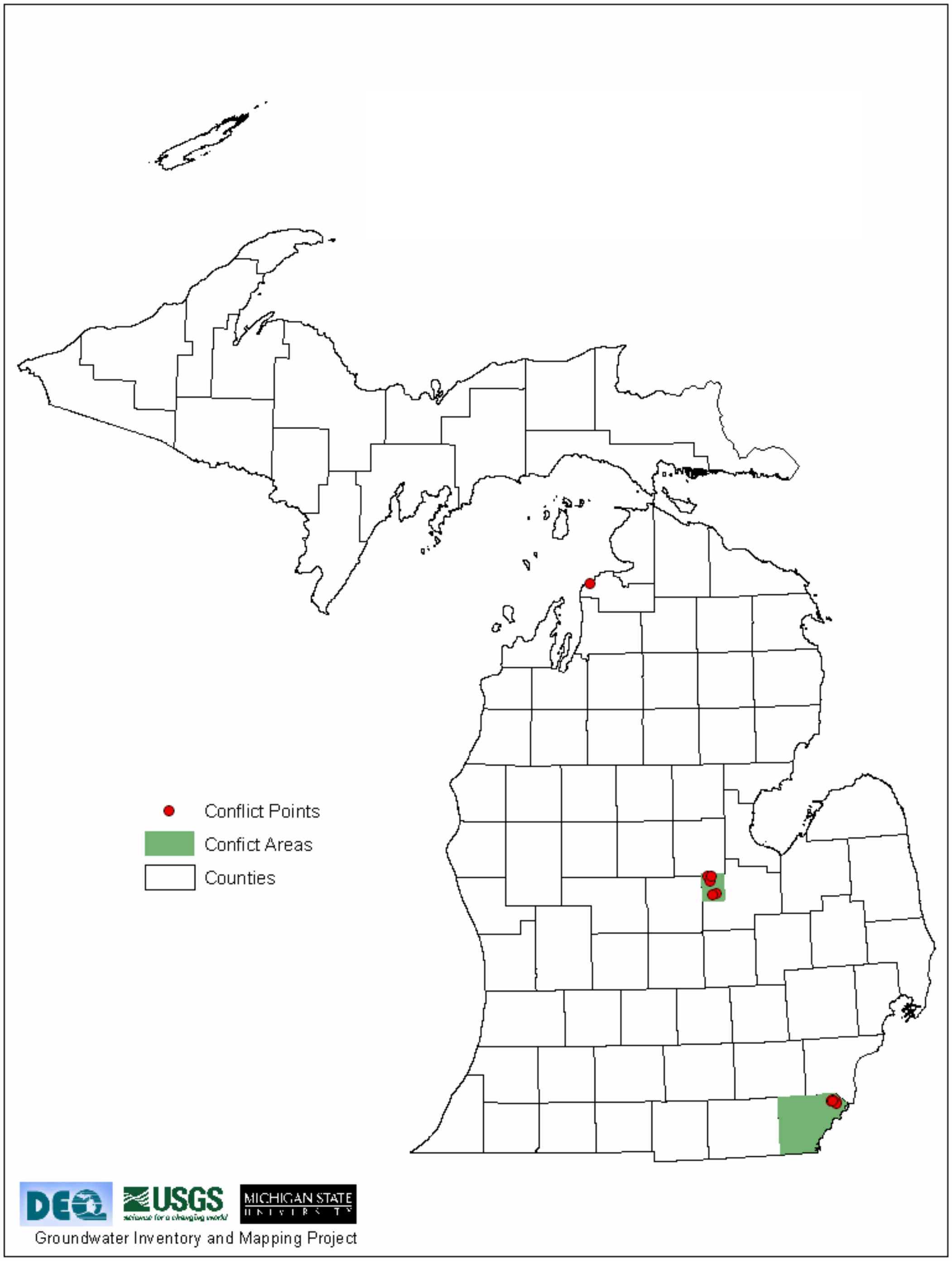

Figure 4.6.1. Designated water use conflict areas and complaint locations as of July, 2005.

4.7(§f) Trout Lakes and Streams and Groundwater-dependent Resources on the Natural Features Inventory

Under the authority of Section 48701(m), as amended, being Sections 324.48701(m) of the Michigan Compiled Laws, the Director of the Department of Natural Resources on October 12, 2000, ordered that certain lakes and streams or portions of streams be designated as trout lakes or trout streams. This order was assigned number FO-200.02 (*Designated Trout Lakes for the State of Michigan*) and FO-210.01 (*Designated Trout Streams for the State of Michigan*) and is available on the MDEQ web site at: http://www.deq.state.mi.us/documents/deq-rrd-TroutLakes.pdf (last accessed on July 5, 2005). Maps of these designated water bodies were downloaded from the Michigan Center For Geographic Information web site where they are housed under the "State geographic extent, Plant and Animal Locations" folder (MDIT, 2005). The designated trout lakes and streams are shown in Figure 4.7.1.

The Michigan Natural Features Inventory (MNFI) is a cooperative program of Michigan State University Extension and the Michigan Department of Natural Resources (http://web4.msue.msu.edu/mnfi/). Their mission is to identify, evaluate and map the locations of Michigan's rarest species and exceptional examples of natural communities and to provide that information to both the public and private sectors for decision-making that affects Michigan's biological diversity. MNFI was established in 1980 and manages the continuously-updated Biological and Conservation Database.

MNFI's Biological and Conservation Database lists and describes the 74 natural communities currently recognized by the Michigan Natural Features Inventory (Table 4.7.1). Information from this database cannot provide a definitive statement on the

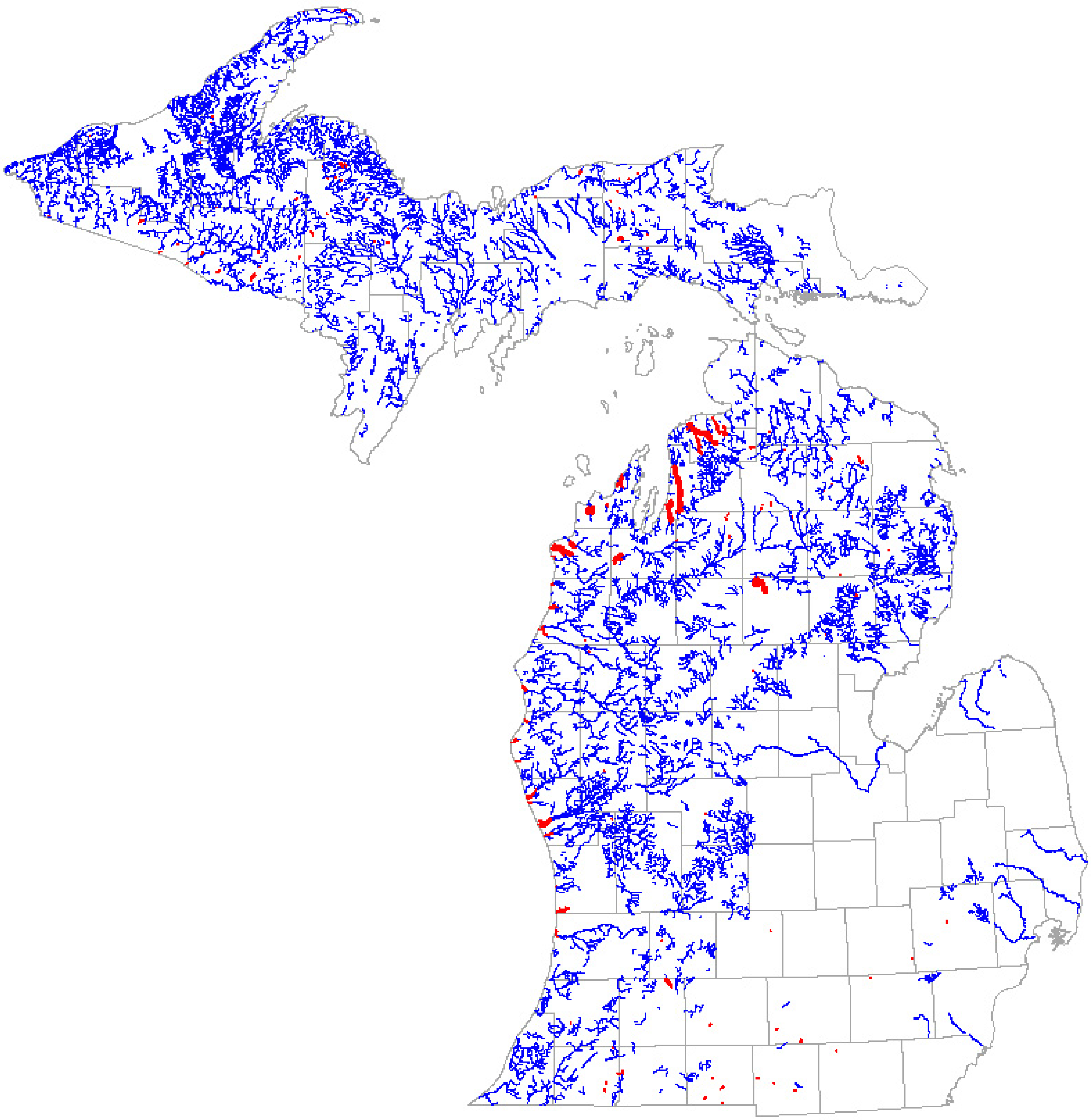

Figure 4.7.1. Designated trout lakes and streams (MDNR, October, 2000).

Table 4.7.1. MNFI List of Community Types (* = groundwater dependent)

Palustrine

Marsh

*__Submergent marsh__
*__Emergent marsh__
*__Great Lakes marsh__
*__Northern wet meadow__
*__Southern wet meadow__
*__Inland salt marsh__
*__Intermittent wetland__
*__Coastal plain marsh__
*__Interdunal wetland__

Prairie

*__Lakeplain wet prairie__
*__Lakeplain wet-mesic prairie__
*__Northern wet-mesic prairie__
*__Wet prairie__
*__Wet-mesic prairie__

Fen

*__Prairie fen__
*__Northern fen__
*__Patterned fen__
*__Poor fen__

Bog

Bog
Muskeg

Forest

Poor conifer swamp
*__Rich conifer swamp__
*__Relict conifer swamp__
*__Hardwood-conifer swamp__
*__Northern swamp__
*__Southern swamp__
*__Southern floodplain forest__

Shrub

*__Northern shrub thicket__
*__Southern shrub-carr__
*__Inundated shrub swamp__

Palustrine/Terrestrial

*__Wooded dune and swale complex__
Boreal forest

Terrestrial

Forest

Mesic southern forest
Dry-mesic southern forest
Dry southern forest
Mesic northern forest
Dry-mesic northern forest
Dry northern forest

Savanna

Lakeplain oak openings
Bur oak plains
Oak openings
Oak barrens
Oak-pine barrens
Pine barrens
Great Lakes barrens
Northern bald

Prairie

Lakeplain mesic sand prairie
Mesic prairie
Hillside prairie
Mesic sand prairie
Woodland prairie
Dry sand prairie

Primary

Open dunes
Sand/gravel beach
Cobble beach
Alvar grassland
Bedrock glade [5 subtypes]
Bedrock lakeshore [4 subtypes]
Cliff [8 subtypes]
Sinkhole

Subterranean

Cave

presence, absence, or condition of the natural features in any given locality, since much of the state has not been thoroughly surveyed for their occurrence and the conditions at previously surveyed sites are constantly changing.

According to Mr. Michael Kost, MNFI Ecology Program Leader, 28 of the natural communities in the Biological and Conservation Database are considered as “groundwater dependent” (shown with an asterisk and bold font in Table 4.7.1). All but three of the palustrine communities are groundwater dependent. The bog, muskeg and poor conifer swamp communities are not groundwater dependent, since they are all defined in the database as “ombrotrophic”, meaning that they receive nutrients solely from rain water. Of the two palustrine/terrestrial communities in the database, only the wooded dune and swale complex are considered to be groundwater dependent.

Vector polygon maps of these 28 botanical communities were received from MNFI. In order to generalize the exact location and extent of these communities (as requested by MNFI) the vector polygons were intersected in GIS software with the quarter-quarter (40 acre) grid maps from the Michigan Center For Geographic Information (MDIT, 2005c). The groundwater dependent natural resources in the MNFI Biological and Conservation Database are shown in Figure 4.7.2.

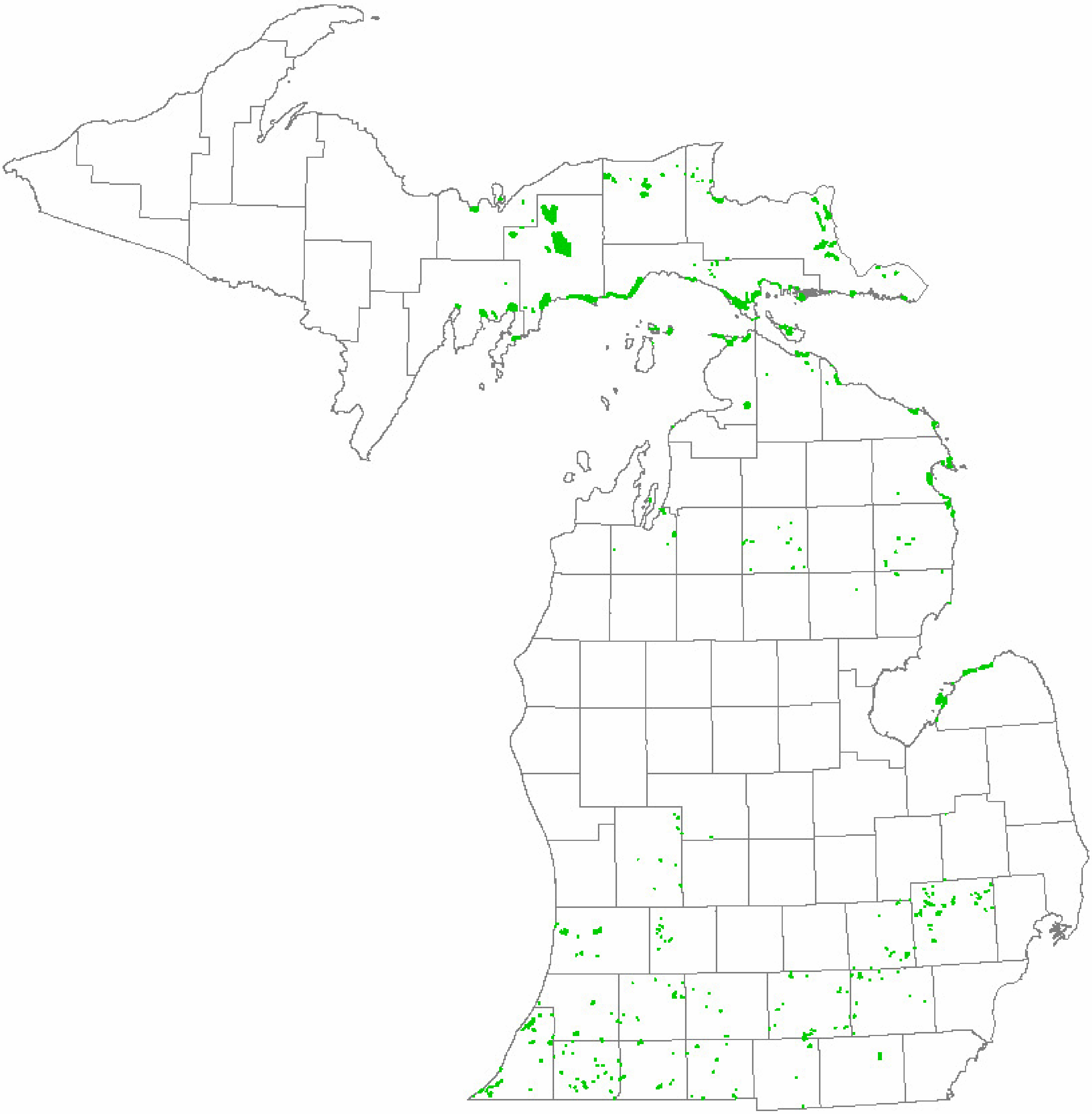

Figure 4.7.2. MNFI groundwater dependent natural resources

4.8 (§g) Water Use Reported to Michigan Department of Environmental Quality

Michigan's Water Use Reporting Program is a strategic effort to inventory, analyze, and report baseline information for major water uses in Michigan. The primary goal of the program is to inform the public of the value of the shared water endowment of the Great Lakes Basin.

Recognizing the need for a more integrated approach to managing water resources, the states and provinces surrounding the Great Lakes signed the Great Lakes Charter in 1985. Member jurisdictions include the states of Michigan, Indiana, Illinois, Minnesota, New York, Ohio, Pennsylvania and Wisconsin, as well as the Canadian provinces of Ontario and Quebec. The overall purpose of the Charter is to protect and manage the water resources within the Great Lakes Basin as a shared resource. Specific management principles recognize the Great Lakes as an integrated ecosystem, commit the states and provinces to cooperatively manage surface and ground water resources, and unify the region against water diversions that would result in significant adverse impacts on lake levels, in-basin water uses, or the Great Lakes ecosystem. Key provisions of the Great Lakes Charter require the states and provinces to collect water use information for thermoelectric power generation, industrial, public water supply, irrigation, and other sectors to provide a scientific basis for managing the water resources in the region.

In Michigan, the Water Use Reporting Program is implemented by the Michigan Department of Environmental Quality under the authority of Part 327 of the Natural Resources and Environmental Protection Act (1994 PA 451, as amended). The Water Use Reporting Program requires thermoelectric power plants, self-supplied industrial facilities and non-agricultural irrigators to report their water use to the Michigan Department of Environmental Quality each year. Water use information for public water supply systems is required under the authority of Part 15 of the Administrative Rules for the Michigan Safe Drinking Water Act (1976 PA 399, as amended). Agricultural irrigation was previously estimated using a computer model that utilized weather, soils, and other resource data, including crop and acreage information reported in the federal Census of Agriculture. Beginning in 2004, under 2003 PA 148, farms must report their water use to either the Michigan Department of Agriculture or the Michigan Department of Environmental Quality.

Under Part 327 of NREPA (1994 PA 451, as amended), power generation plants, self-supplied industries and golf course irrigators must register with the Michigan Department of Environmental Quality and report their water use if they have the *capacity* to withdraw over 100,000 gallons of water per day over any 30-day period. Farms with this capacity have the option of reporting to either the Michigan Department of Agriculture or the Michigan Department of Environmental Quality. A water withdrawal capacity of 100,000 gallons per day is equivalent to a pumping capacity of 70 gallons per minute. Registration is based upon the total pumping capacity of a facility's system, regardless of how much water is actually withdrawn during a given year. Actual reported water withdrawals may be lower. A summary of the 2003 reported water use by the non-agricultural sectors is shown in Figure 4.8.1.

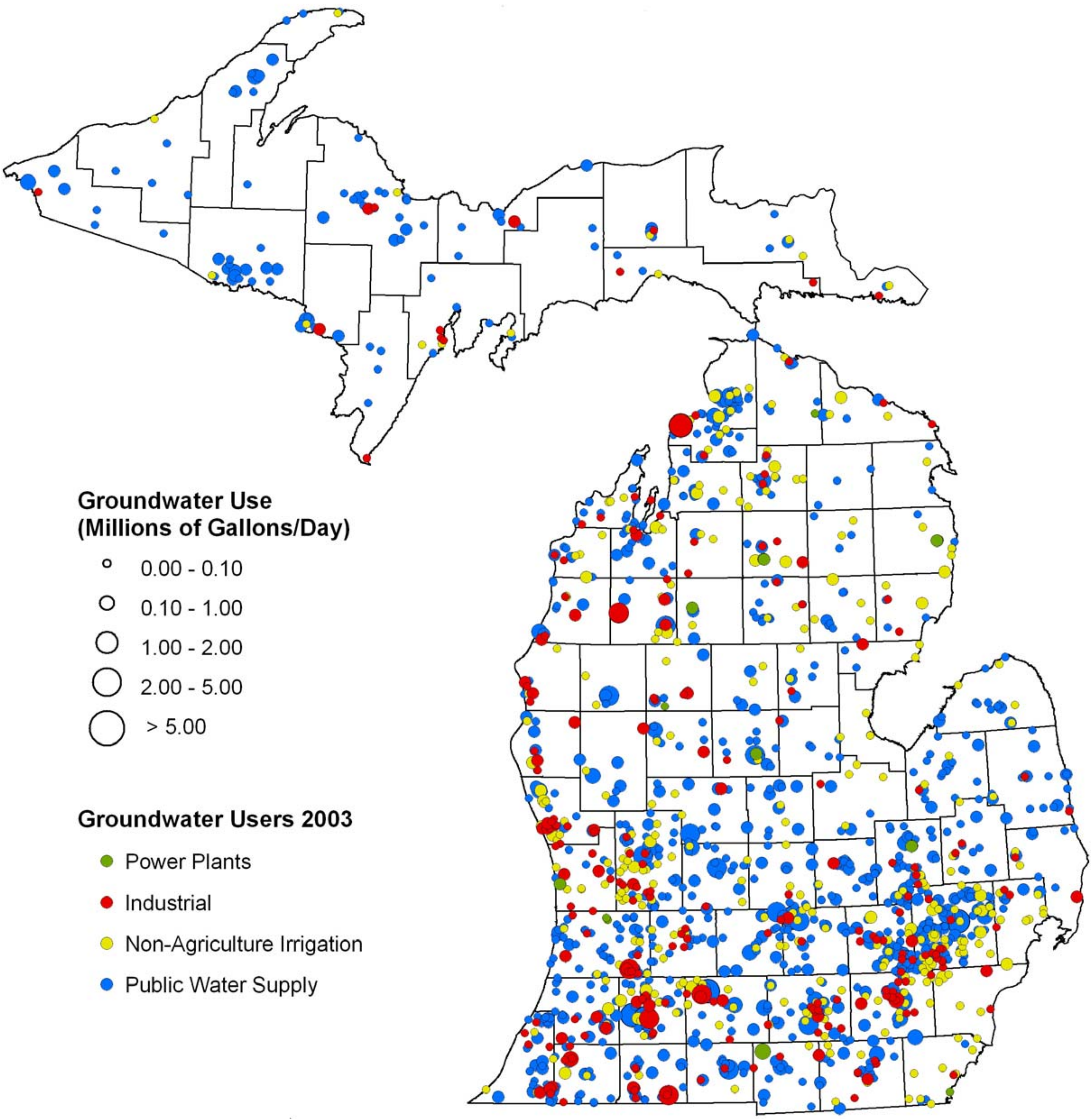

Figure 4.8.1. Non-agricultural water users and their use for 2003 (the most recent data available).

4.9 (§h) Agricultural Water Use Reported to Michigan Department of Agriculture

Water use was reported to the MDA by agricultural producers in the state that met the water pumping capacity thresholds (70 gpm) during the 2004 calendar year. At least 90 percent of the reported water use was for irrigation. This agricultural water use, aggregated by political township as required by P.A. 148, is shown in Figure 4.9.1. **It is estimated that 27% of the reported water use was withdrawn from surface water sources.** Michigan and the other Great Lakes states have agreed that 90 percent of agricultural irrigation water use is consumptive. The proportion of other agricultural water uses that is consumptive varies by use.

Water use reporting forms were mailed to all agricultural producers who registered with the MDA. Forms were also made available on the MDA web site. Data mailed back to MDA were entered into a database and water use was aggregated by political township. Water use was reported in a variety of units (gallons, acre-feet, and acre-inches), but these were converted to millions of gallons per day (MGD) for consistency with other water use reporting. Obvious errors made by reporting producers were corrected; otherwise, all data were entered as reported.

Agricultural water withdrawals typically occur only during the period May through September, so to be consistent with the non-agricultural water users, the mapped values are annualized averages. As mentioned above, the reported agricultural water use data include both groundwater and surface water withdrawals. As a result, comparisons with the facilities shown on Figure 4.8.1 require careful scrutiny. An MDA comparison

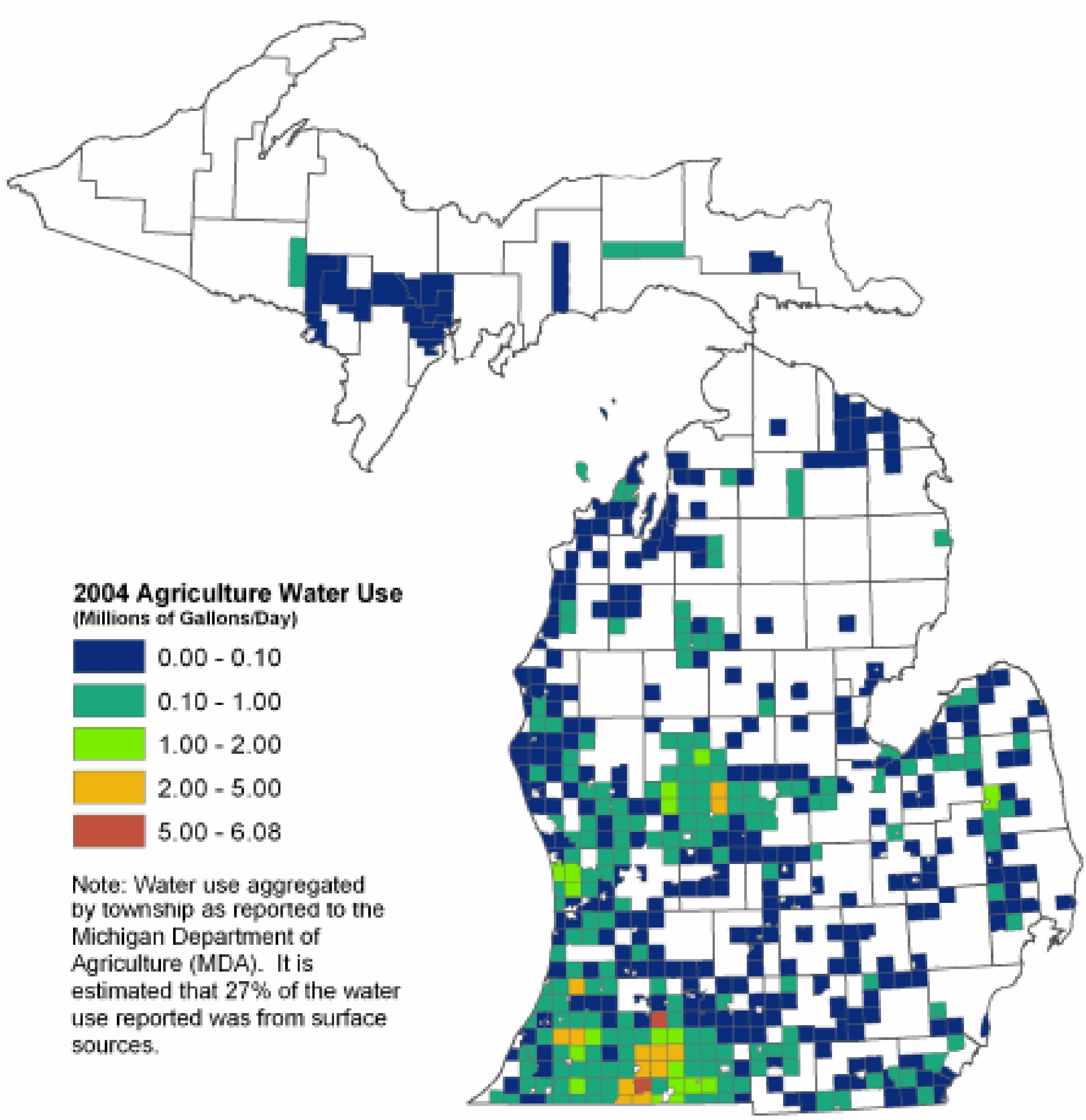

Fig 4.9.1. Total agricultural water use, by township, as reported to MDA. It is estimated that 27% of the reported water use was withdrawn from surface water sources.

of the 2004 reported agricultural water withdrawals with the 2002 National Agricultural Statistics Service (NASS) irrigation survey reveals that MDA received reports covering 69.7% of the irrigated acres tabulated by NASS. By comparison, the non-agricultural groundwater use reported in Section 4.8.1 has an estimated reporting rate exceeding 90%.

Chapter 5 Groundwater Data Inventory and Bibliography

5.1 Methods

In fulfillment of the mandate by Section 32802 (1) of P.A. 148 to "collect and compile groundwater data into a statewide groundwater inventory ..." the project searched the available literature for relevant documents. An electronic search for theses, journal articles, abstracts, conference presentations/papers, and government documents describing groundwater characteristics in Michigan was completed using various sources and databases.

An online search within the U.S. Geological Survey Publications Warehouse (http://infotrek.er.usgs.gov/pubs/) retrieved 612 documents about Michigan resources. Out of these, over 150 were applicable to the guidelines established for the project (i.e., groundwater inventory publications including water supply, water use, groundwater withdrawals, aquifer characteristics and water resources. Over 60 publications were either downloaded as Adobe Acrobat pdf files, or converted to that format (the U.S. Geological Survey Publication Warehouse utilizes the "Document Express with DjVu" software [LizardTech, Seattle, WA, USA]).

Online searches using the scientific databases, GEOREF and GEOBASE, were also completed for various water-related publications and documents. Accessing the MSU library's MAGIC Online Catalog and Michigan eLibrary (MeL) indicated whether the various documents were available at various libraries. The majority of the documents were available at the MSU library in the U.S. Geological Survey section of the documents library. All of the qualifying, available documents were entered into the bibliography and were prioritized for digital scanning.

5.2 Overview of the Inventory

Over 220 documents and applicable map plates were digitally scanned as pdf or tiff files, and are available on the project web site (gwmap.rsgis.msu.edu/). The full bibliography containing 464 citations is also available on the project web site and is included as Appendix 8.9.

The scanned documents were categorized by a USGS format within the Groundwater Information Database in order to support web-based queries. Several search options are available on the wed site. Publications cited in the summaries, as well other publications, can be accessed and downloaded. Aquifer data or water quality data from within these publications has been extracted and entered into the searchable database as well.

As shown in Figure 5.2.1, a summary is available for each county, as well as county-specific hydrogeologic data, if available. The county summaries provide an overview of the groundwater resources in each county and reference the watersheds located within the county. The general nature of the glacial and bedrock aquifers beneath the county is also described. For the queried county, a table lists the following parameters, if available: aquifer type used—glacial and/or bedrock, range of transmissivity and storativity, and water use data in the public supply, domestic, irrigation, livestock, industrial and thermoelectric sectors.

The “Find reports” section can be used to retrieve publications by location (i.e., Statewide, Upper or Lower Peninsula or County), by author, by watershed name or by 8-digit Hydrologic Unit Code (HUC). Each of these query sections returns a table format that includes the title, author(s), and publication attributes.

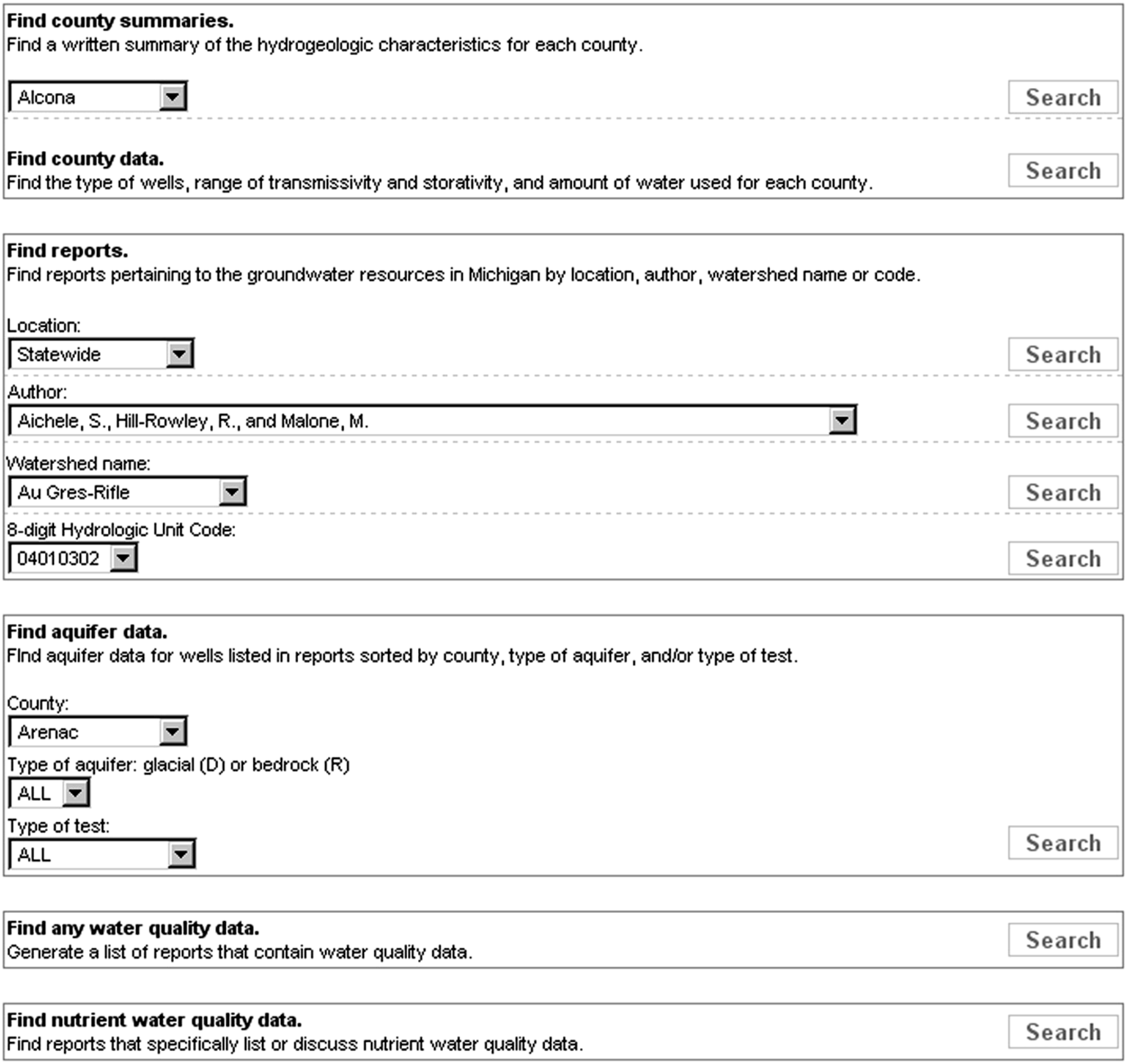

Figure 5.2.1. Groundwater inventory query page from the GWIM web site.

The "Find aquifer data" search window returns a list of the wells referenced in publications germane to the search area that includes the following parameters, if available: Publication Reference, Well ID, County, Township, Tier-Range-Section-Quarter-quarter, X and Y coordinates, Aquifer Type, Lithology, Type of Pump Test, Date of Test, Pumping Duration, Well Diameter, Specific Capacity, Transmissivity, Storage Coefficient, Hydraulic Conductivity and any notes about the values for these wells.

The "Find water quality" data query returns a table that lists the publications germane to the search area that contain water quality information in the following categories: nutrients, organics, major inorganics, minor trace elements and inorganics, physical properties, and radiochemicals.

5.2.1 Copyright Information

The various publications on the web site have been posted with the kind permission of the rights holders. The public may download and print a single copy for private study, or download a master and reproduce multiple hard copies for use in nonprofit educational and training activities, so long as the materials are distributed to the students/participants at a cost not to exceed that of the photocopies themselves. The public may link to any of the materials on the web site without further permission. The rights holders reserve all other rights, and these materials may not be further reproduced in any form or by any means, including for-profit photocopying, e-mail or posting on listservs, or utilized by any information storage and retrieval system, without written permission from the copyright holder. The project made every effort to seek permission to use all borrowed material that appears on this web site. The materials published by the United States Geological Survey are in the public domain and may be copied and distributed freely.

Chapter 6 Distributing the Groundwater Maps to the Public

The inventory and map products are available to end-users in four ways. A web-based mapping site, hosted by MSU (**gwmap.rsgis.msu.edu**), is the primary distribution point (Figures 6.1 and 6.2). Some digital data are also available for download from this site. The digital map data (requires GIS software to view them) may be downloaded through the State of Michigan, Center for Geographic Information (www.michigan.gov/cgi). Digital data for a county or other custom area (e.g., watershed) on a CD or DVD for use with GIS software is also available at cost of reproduction from RS&GIS at MSU.

The ***Map Image Viewer*** software (geopathway.com/), an easy-to-use GIS software package for viewing and analyzing spatial data, is delivered with a county of geospatial data, including the groundwater mapping products. There is a charge for this product for users other than local health departments and the DEQ.

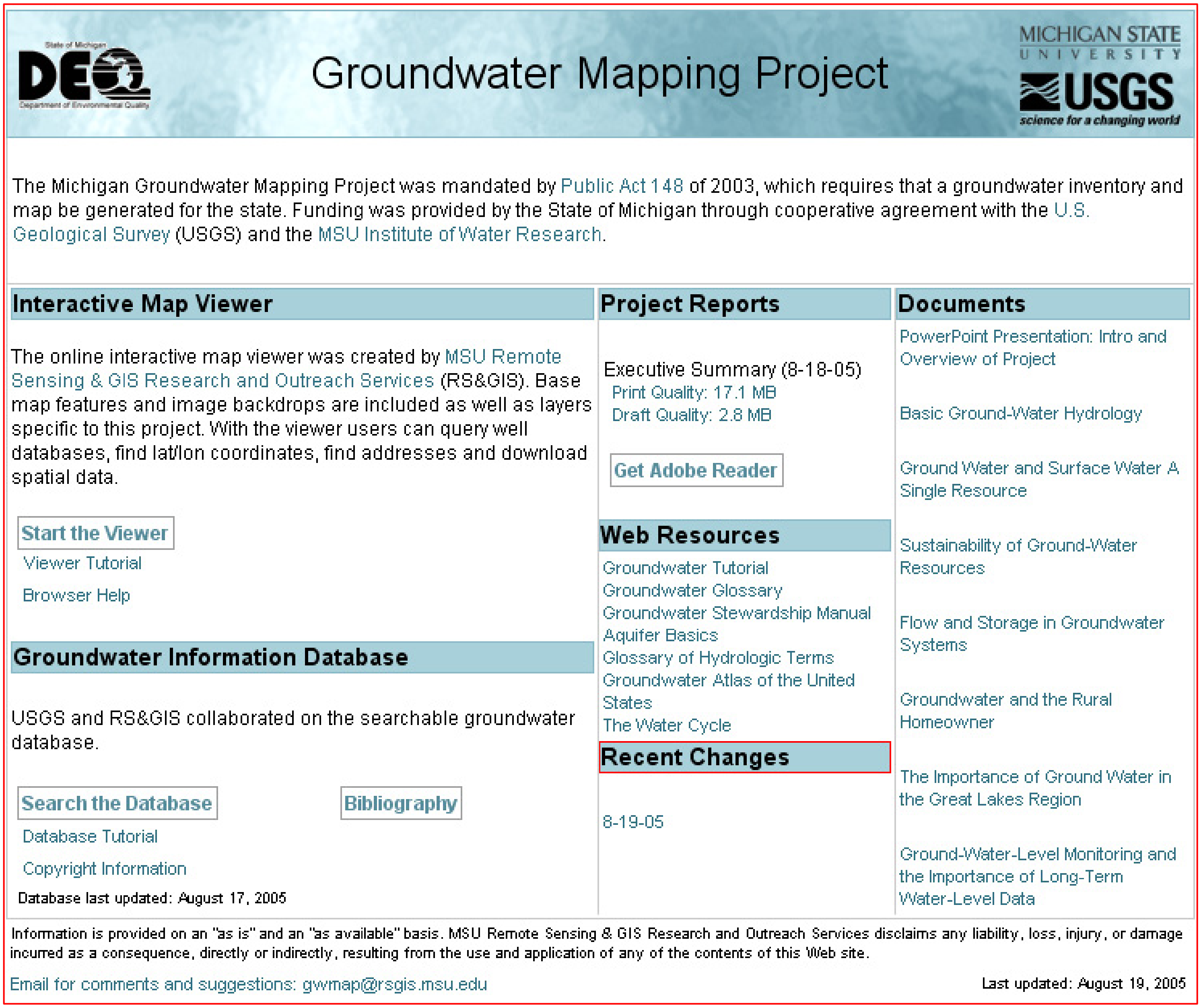

Figure 6.1. Homepage of the Groundwater Mapping Project web site.

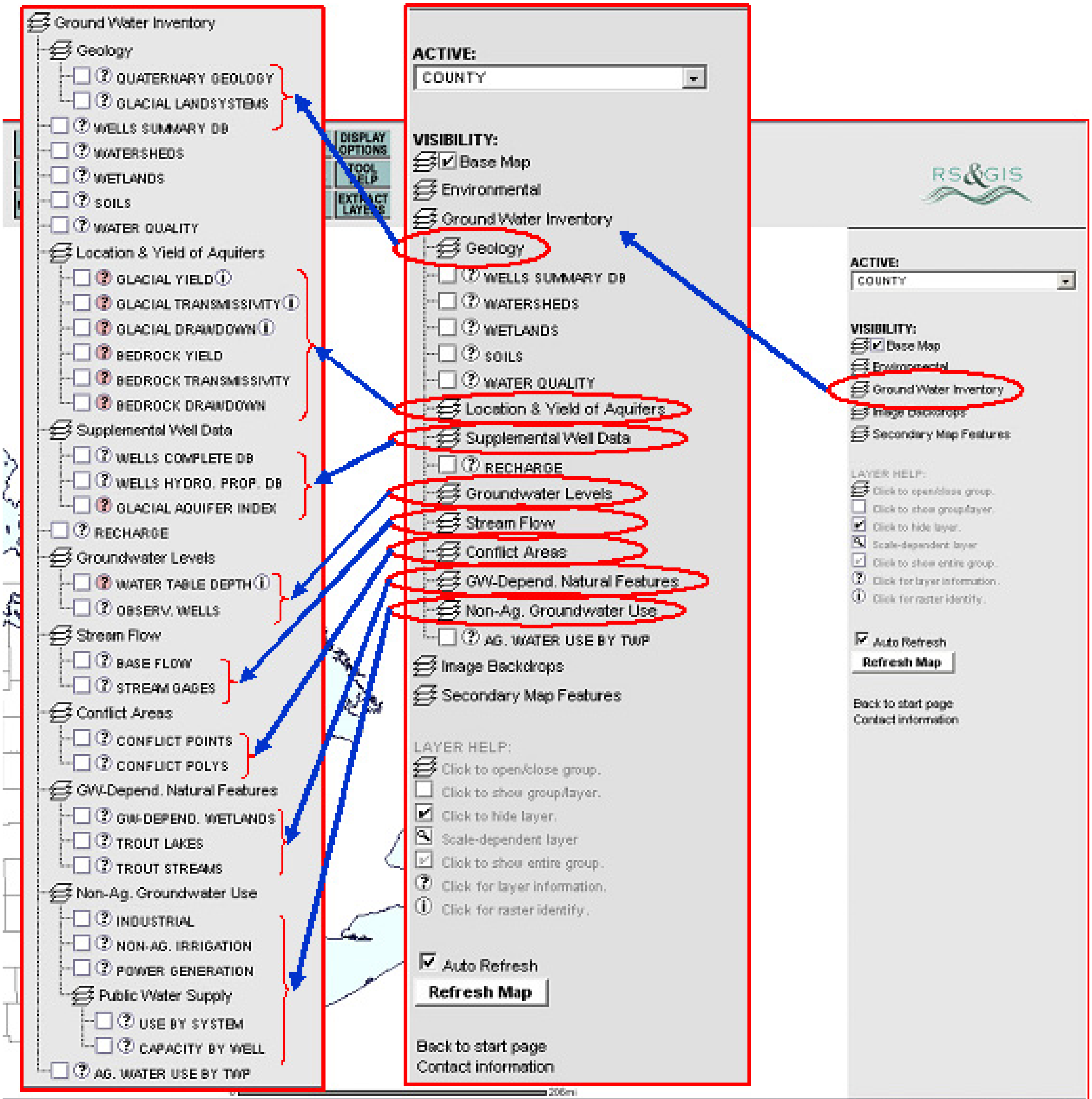

Figure 6.2. Table of contents for the interactive mapping service on the Groundwater Inventory and Mapping Project web site.

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MDIT. 2005c. Center for Geographic Information, Michigan Geographic Data Library, Quarter-quarter (40 acre) grid maps. http://www.dnr.state.mi.us/spatialdatalibrary/sdl/public_land_survey_system/town_range_boundaries/lower_peninsula_town_range.exe) and

(http://www.dnr.state.mi.us/spatialdatalibrary/sdl/public_land_survey_system/town_range_boundaries/upper_peninsula_town_range.exe

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Chapter 8 Appendices

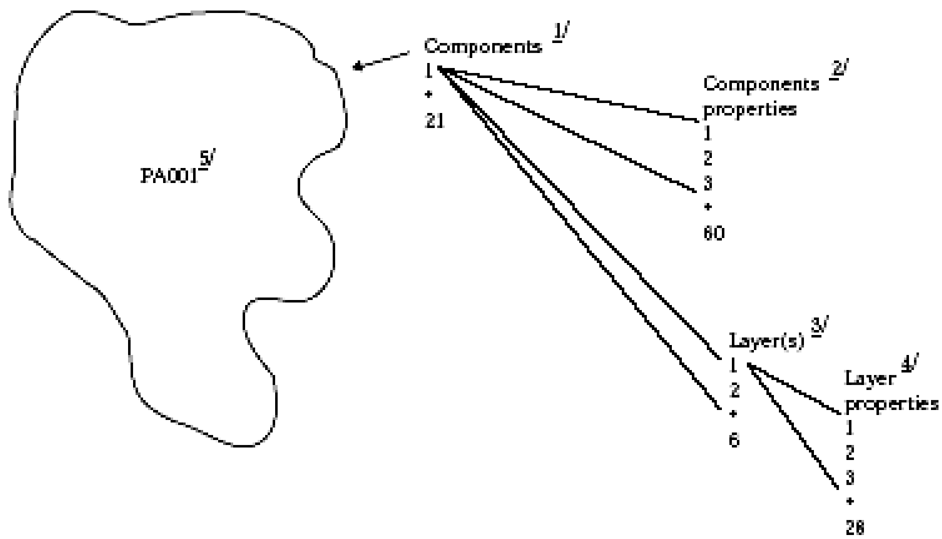
8.1 Data Processing Procedure for Determining the Dominant Soil Texture and Soil Drainage Class from the STATSGO Soil Association Data Base.

In STATSGO, each map unit can have multiple components and each component can have multiple layers (Figure 8.1). Therefore, the analysis must begin at the lowest level in the schema and work back to the highest level. The order from the bottom to the top is layer, comp (component), and mapunit (map unit) tables (Figure 8.2). The layer table is related to the comp table by muid (map unit identifier) and seqnum (sequential number), which is the component number. The comp table is related to the mapunit table by muid, and the mapunit table is related to the map data by muid. Other tables such as compyld (component yield) or interp (interpretation) are on the same level with comp and relate to the comp table with muid and seqnum.

The comp table can be considered as the hub through which all analyses pass (Figure 8.2). This is necessary to acquire the comppct (component percent) of each map unit that meets a criterion or criteria. Because there are several layers in the layer table for each component in the comp table, a decision must be made as to how the data should be handled. Methods include selecting for the presence or absence of a property, selecting a specific layer, or aggregating the data by calculating a weighted average or the sum of the weighted average.

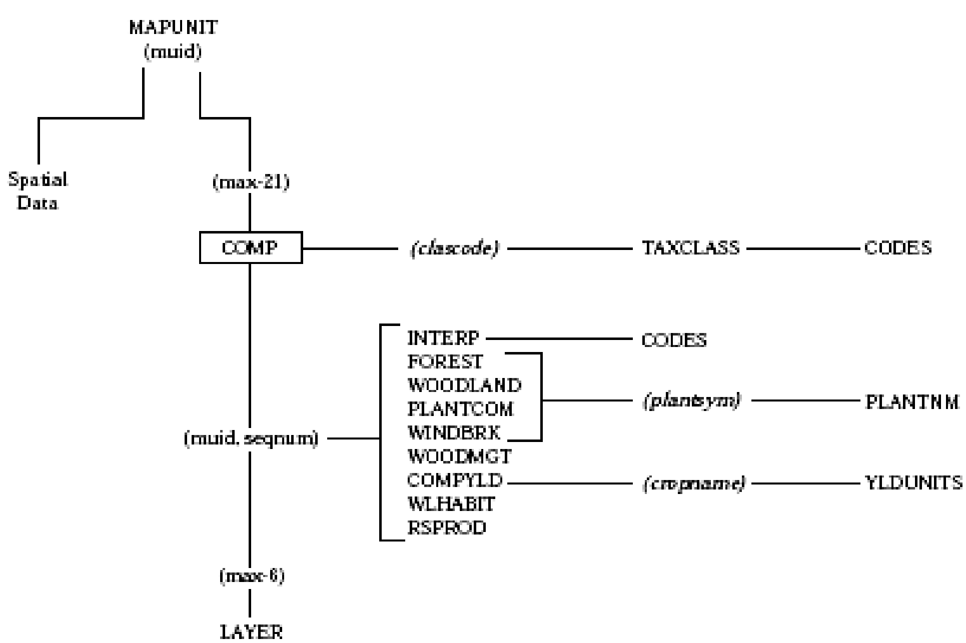
An example for selecting for the presence of a property is locating all map unit components that have a pH of less than 4.5 and aggregating the component percents by map units. An example of selecting a specific layer is selecting the surface layer for

Figure 8.1 STATSGO map unit.



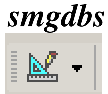
1 STATSGO map units consist of 1 to 21 components.
2 For each component, there are 60 soil properties and interpretations in 84 different data elements (component tables), for example, flooding.
3 For each component, there are 1 to 6 soil layers.
4 For each layer, there are 28 soil properties; for example, percent clay.
5 A map unit identifier created by concatenation of the two-character State FIPS code and a three-digit Arabic number. It uniquely identifies a map unit within a State.

Figure 8.2. STATSGO table relationships.

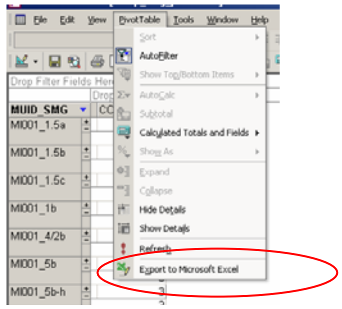


organic matter content and averaging the low and high values. A weighted average can be calculated for clay. The low and high values can be averaged and multiplied by the layer thickness and then divided by the total soil thickness. The sum of the weighted average can be calculated for available water capacity. The low and high values can be averaged, multiplied by the layer thickness, and then summed. These methods reduce a many-to-one relationship to a one-to-one relationship.

The processing steps used by this project were as follows:

- Import comp.dbf into Microsoft Access®. Delete all fields except MUID, MUIDSEQNUM, COMPNAME, and COMPPCT.
- Import mi_series_smgs.dbf and rename the table smg.
- Create a "make table query" to join smg.dbf to comp.dbf using "SERIES" and "COMPNAME" as the join fields. Add all the fields from comp.dbf and only the Mi_smg field from the smg.dbf. Name the table "***smgdbs***" and rename the Mi_smg field to SMG.
- Create a new field called MUID_SMG.
- Concatenate the MUID and SMG fields by using the update query function. The expression should read: [MUID]+"_"+[SMG], which yields MI001_2a.
- To sum the percentages use the Pivot table function.
- Open the ***smgdbs*** table in Pivot View Table using the design view dropdown button. 
- Click the field list button, top right-hand side of the screen.  Drag the MUID_SMG field to the area that says "drop row fields here", located at the far left of the screen. Drag the COMPPCT field to the middle of screen.
- Highlight the COMPPCT field by clicking on the COMPPCT name. Use the sum button, located in the middle of the pivot table menu, to sum all the fields that are the same.

- Click on the PivotTable dropdown menu and then Export to Microsoft Excel®. Copy, paste, and save the table in a new workbook.



- Import the Excel spreadsheet into Access and name it ***Total PCT***. Create a table query and join the ***Total PCT*** table with ***smgdbs*** by using the MUID_SMG fields as the join fields. Name the new table ***smgdbs_pct***.

- To automatically delete the duplicate MUID_SMG records, use the index property "Yes no duplicates" in design view.

  - Copy the ***smgdbs_pct*** table. Click paste, structure only, and name the new table ***smgdbs_nosmgdups***.

  - Open the new table (***smgdbs_nosmgdups***) in design view. Click on the MUID_SMG field. In field properties at the bottom of the screen click on the index field property and choose "Yes No Duplicates".
  - Copy all the data from ***smgdbs*** and paste it in ***smgdbs_nosmgdups*** table. Click yes to all the warnings that pop up on the screen.

- Delete all the blank smg records in the ***smgdbs_nosmgdups*** table. These records did not have any soil management groups associated with them; therefore, these records will not be queried.

- Create another unique field by concatenating the MUID and Total PCT fields using the procedures given above for MUID_SMG. Name the new field MUID_PCT.

- The maximum duplicate percentages for each individual MUID need to be identified. Use the "find duplicate query wizard" by clicking queries at the right of the screen, click new, and find duplicate query wizard. Follow the wizard by using the MUID_PCT field to look for duplicates. After the query is created in the wizard, click design view and create a "table query". Name the new table ***smgdbs_pctdups***.

The next several steps will describe how to query for each MUID's maximum percentage. To begin, the table needs to be ordered by descending Total PCT and ascending MUID. This step allows the maximum percentage to be at the beginning of every new MUID number. Next, the index field property "Yes No Duplicates" is used to delete all MUID duplicates. MS Access will choose the first MUID, which in this case, is the maximum percentage.

- Create a table query using the ***smgdbs_nosmgdups*** table. Add all the fields to the query, click the descending tab on the sort drop down menu under Total PCT and choose ascending under the MUID field. Name the new table ***smgdbs_inorder***.

- Copy the ***smgdbs_inorder***. Click paste, structure only, and name the new table ***MaxPCT***.

- Open the new table (***MaxPCT***) in design view. Click the MUID_PCT field, in field properties at the bottom of the screen click the index field property and choose "Yes No Duplicates".

- Copy all the data from ***smgdbs_inorder*** and paste it in the ***MaxPCT*** table. Click yes to all the warnings that pop up on the screen.

In some instances, two different textures or drainage classes can have the same or similar dominant percentages for the same MUID. This is important to acknowledge because each MUID should include all the drainage classes or textures that are the majority composite of the polygon.

- To identify the duplicates create another query by adding the ***MaxPCT*** and ***smgdbs_pctdups*** tables and use the MUID as the joining field. Highlight the line that joins the two tables, click on the view dropdown menu, and choose include all records from ***MaxPCT*** and only those that match ***smgdbs_pctdups***. Highlight and drag all of MaxPCT's fields into the query. Then, drag the MUID field from ***smgdbs_pctdups***. Uncheck the ***smgdbs_pctdups*** MUID field. Type "is not null" in the criteria for the MUID field. Create a table query and name it MaxPCT_dups.

The SMG field in the ***MaxPCT*** table will be the texture or drainage lable field, therefore, if duplicates are found, change the SMG field to represent all duplicates associated with the MUID. For example, MI001 has two major soil textures 5 and 4. In the SMG field, type 5&4.

Within the same MUID, the soil texture or drainage class may have percentages that are not exactly the same but are close enough that they need to be included as part of the texture or drainage label. Therefore, all dominate soil textures or drainage classes within the same MUID need to be identified and labeled accordingly.

All dominate soil textures or drainage classes for each MUID were identified using the basic logic shown in Table 8.1.1. The ***smgdbs_inorder*** was extracted from MS Access® and imported into MS Excel®. The logic formula (Table 3.8) was coded in MS Excel® to rank and label the soil texture or drainage class for each MUID.

Table 8.1.1. Soil and Drainage Class Logic

Line #	Logic	Symbol Code	Rank
1	If 1 $\geq$ 75%	1	1
2	If 1 $\geq$ 51% and 2 $\geq$ 24% and 3 < 19%	1+2	2
3	If 1 $\geq$ 51% and 2 $\geq$ 24% and 3 $\geq$ 19%	1+2_3	3
4	If 1 $\geq$ 25% and 2 $\geq$ 25% and 3 < 20%	1_2	4
5	If 1 $\geq$ 20% and 2 $\geq$ 20% and 3 $\geq$ 20%	1+2+3	5
6	If 1 $\geq$ 20% and 2 $\geq$ 20% and 3 $\geq$ 15%	1_2_3	6
7	If 1 $\geq$ 51% and 2 $\leq$ 24%	1*	7
8	If 1 $\geq$ 33% and 2 $\leq$ 20%	1**	8
all else		Mixed	0

Logic assumes an ordered ranking of soil texture or drainage class percentage where soil texture or drainage class # 1 $\geq$ # 2 $\geq$ # 3.

Symbol Code: The logic (Table 8.1.1) was coded in MS Excel® using the "if" statement shown in Table 8.1.2a. This code can be used for both soil texture and drainage. The symbol code "if" statement output was typed in column "E" of the attribute table as shown in Table 8.1.3. The symbol code in the logic represents the first, second, and third soil texture or drainage class within the same MUID. For example, in Table 8.1.3, MUID # MI001 soil drainage #1 = b, which occupies 43% of the polygon; soil drainage #2 = c, which occupies 24% of the polygon; and soil drainage #3 = a, which occupies 7% of the polygon. Therefore, if the logic above is followed the soil texture is labeled Mixed and the rank is 0.

Rank: The "if" statement shown in Table 8.1.2b determined the ranking logic and recorded this in column "F" of the attribute table as shown in Table 8.1.3. The code can be applied to either drainage class or soil texture. The soil texture or drainage class ranking corresponds to the logic line coding. Duplicates were ranked "22" and coded differently. The logic was ranked to make it easier for the user to query specific logic lines in ArcView or MS Access®.

Table 8.1.2. <u>MS Excel</u>® coding statements.

a. Symbol Code “if” Statement.

```
=IF(C2>=75,D2,IF(AND(C2>=51,C3>=24,C4<19),D2&"+"&D3,IF(AND(C2>=51,C3>=24,C4>=19),D2&"+"&D3&"_"&D4,IF(AND(C2>=25,C3>=25,C4<20),D2&"_"&D3,IF(AND(C2>=20,C3>=20,C4>=20),D2&"+"&D3&"+"&D4,IF(AND(C2>=20,C3>=20,C4>=15),D2&"_"&D3&"_"&D4,IF(AND(C2>=33,C3<20),D2&"**","MIXED")))))))
```

b. Ranking “if” Statement.

```
=IF(C2>=75,1,IF(AND(C2>=51,C3>=24,C4<19),2,IF(AND(C2>=51,C3>=24,C4>=19),3,IF(AND(C2>=25,C3>=25,C4<20),4,IF(AND(C2>=20,C3>=20,C4>=20),5,IF(AND(C2>=20,C3>=20,C4>=15),6,IF(AND(C2>=33,C3<20),8,"0")))))))
```

Table 8.1.3. Example attribute table for soil texture and drainage ArcView shape files.

A	**B**	**C**	**D**	**E**	**F**
MUID 1	MUID 2	TOTAL PCT	drainage	SYMBOL	RANK
MI001	MI001	43	b	MIXED	0
	MI001	24	c		
	MI001	7	a		
MI002	MI002	75	c	c	1
	MI002	18	b		
	MI002	2	a		

8.2 Formal Geologic Mapping

The most rigorous approach for developing an aquifer map for the glacial deposits is to first map the glacial geology at an appropriate scale to capture the important heterogeneities caused by glacial deposition processes. This map would then be used to derive an aquifer map based on the distribution of lithology and observed hydrogeologic behavior from the field. Most existing maps of the glacial deposits for Michigan, however, are at too small scale to capture the heterogeneity observed in the field. The Central Great Lakes Geologic Mapping Coalition (a coalition comprised of geologists from the USGS and State Geological Surveys (or equivalent) from Illinois, Indiana, Ohio, and Michigan) published a detailed geologic map of Berrien County, Michigan that illustrates the importance of scale (Stone, 2001). The Berrien County map is published at 1:100,000 scale, but it is a compilation of maps done at 1:24,000 scale. There is more detail in all areas of the map compared to the Statewide Farrand and Bell (1982a) map (Figure 8.2.1). Note, for example, the Qbl deposit (shaded in bright blue) that runs parallel to the present shoreline of Lake Michigan. This deposit is identified as "lake bottom deposits from glacial lake Baroda with pale brown fine sand at the surface locally with laminated gray silt and clay, 3-30 ft thick." The three-dimensional extent of this unit and local continuity of the silt and clay laminations will determine the hydrogeologic importance of this unit. If the clays are continuous, this unit may serve as a local confining layer. In this case, heterogeneities in the unit where groundwater may flow towards Lake Michigan would be very important. If the clays are very discontinuous, however, the unit may not serve as an effective confining layer and local heterogeneities would be less important.

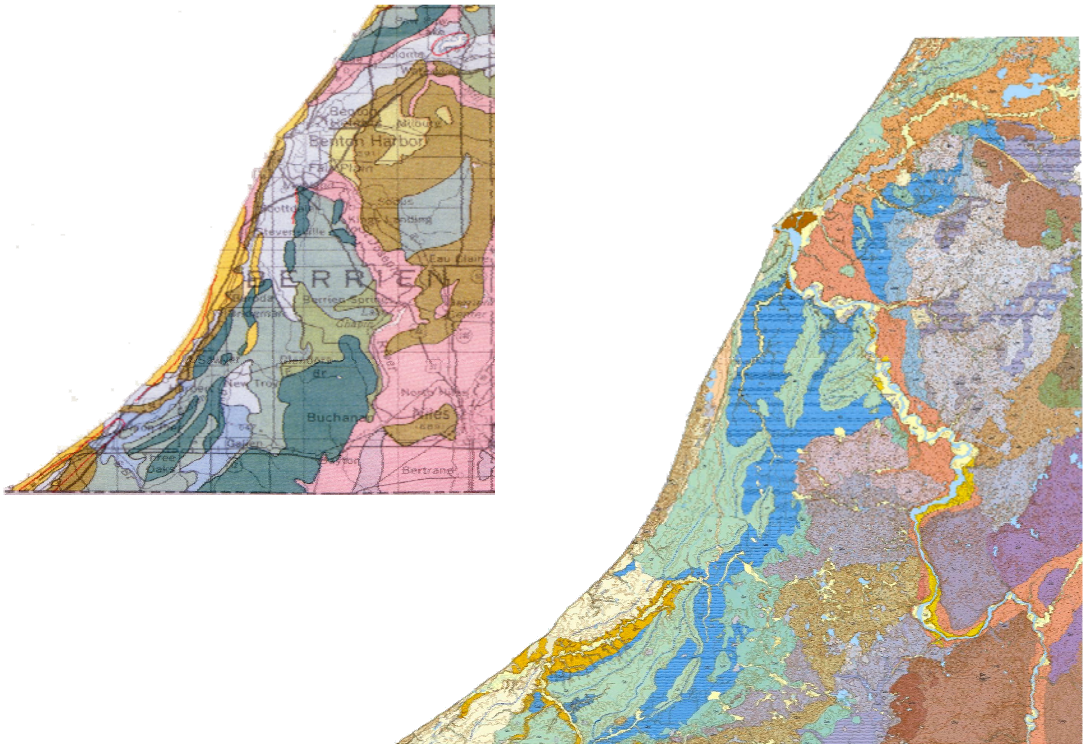


Figure 8.2.1 Surficial Glacial Geology for Berrien County, Michigan as depicted on the Farrand and Bell (1982a) and Stone (2001) maps. The Farrand and Bell (1982a) map is at a 1:500,000 scale and the Stone (2001) map is at 1:100,000 created from 1:24,000 basemaps.

The Berrien County map was developed using the concept of identifying the glacial morphosequences forming the glacial deposits (Stone and others, 1999). Koteff and Pessl (1981) define a morphosequence as

> *"…a continuum of landforms composed of melt-water deposits, from more collapsed forms due to melting ice blocks at the head or upstream parts of outwash, to progressively less collapsed forms downstream. A [morpho]sequence can thus be viewed as a body of stratified drift laid down, layer upon layer, by melt water at and beyond the margin of a glacier, while deposition was controlled by a specific base level. The complexity of the morphologic features depends on the relative number, size, and distribution of detached ice blocks around and over which the sequence was deposited."*

In addition to the map of the surface deposits, a three-dimensional model of the glacial deposits in Berrien County, Michigan will be developed using the morphosequence approach (Stone, U.S. Geological Survey, personal communication, 2003). When the three-dimensional model is complete, the depositional units will then be evaluated to determine the pattern of material deposition, the hydrogeologic facies, within each unit. For example, the material in many morphosequences is graded from coarse to fine away from the past location of the glacier. By considering the depositional processes and using information from the field, a three-dimensional hydrogeologic facies model may be derived from the three-dimensional morphosequence model. This approach is an application of the concepts put forth by Anderson (1989). The notion is that even in this complex geologic environment, if the depositional processes that produced the present-day glacial deposits can be identified, the hydrogeologic characteristics of the deposits may be understood.

The advantage of the morphosequence mapping approach is the geologic rigor that constrains the interpretation of the hydrogeologic characteristics of an area. The approach may help locate important aquifers within deposits that tend to have poor aquifer characteristics (for example, an aquifer formed by a buried channel that is in-filled with sand and gravel). The approach also provides geologic base maps that can be used for a variety of environmental or geotechnical problems including flood plain and sediment transport analysis; sand and gravel exploration; and foundation, highway and structural design.

The disadvantage of the morphosequence mapping approach is that the method is both resource-intensive and time-consuming. Surficial geology of only 8 of the 83 counties in Michigan have been mapped at this level of detail (Sullivan, Detroit News, August 6, 2004), and a full three-dimensional map of the morphosequences from the land surface to bedrock is not yet available for any county. Therefore, the method does not rely on existing data as necessitated by the time frame required for this project. Additionally, most groundwater-resource models have not been developed based on this type of detailed geology, thus the benefit to developing a water-resource-management model with this level of geologic detail is unknown. Finally, the appropriate scale for the mapping is not clear given the desire to quantify water resources. Water-resource evaluation may not require the identification of each three-dimensional morphosequence at the 1:24,000 scale followed by the development of the hydrogeologic facies model. Many of the individual depositional units on the 1:24,000 scale may combine to form aquifers or aquitards, and mapping at a smaller scale focusing on the most important hydrogeologic facies may be more efficient. Conversely, many morphosequences have hydrogeologic heterogeneity at short distances within individual depositional units. Approaches to identify which of these small-scale heterogeneities are important for water-resource management must be developed.

Surficial geologic mapping of the glacial deposits that cover most of Michigan is important to increased development and evaluation of water-resources potential from the glacial deposits. More work also may be required in development of the mapping approach and testing of groundwater models to assess the appropriate mapping scale. The appropriate scale presumably depends on the local complexity of the geologic deposition and therefore may vary across the State. The scale issue must be addressed in order to formulate a water-resource-based work plan to map the State. This type of mapping is certainly a long-range project, but one that is very important to the development of water-resource management for aquifers formed in the glacial deposits of Michigan.

8.3 Linear Regression

Because of the relative success of the Drift Index analysis to generate spatial patterns consistent with Statewide maps of glacial groundwater resources, the lithologies from the *Wellogic* database for public water supply wells were used to predict the reported transmissivity values in the P-1 and RASA databases. The motivation for this approach was that if hydraulic conductivities could be assigned to each lithology, or to groups of lithologies, and calibrated to aquifer-test results in the P-1 and RASA databases, then the calibrated hydraulic conductivity values could be used to estimate transmissivity at all of the remaining wells with well records reporting glacial deposit lithologies in the *Wellogic* database. Two regression tests were performed. The first grouped all glacial deposit lithologies into three classes: coarse, medium, and fine, and attempted to determine a hydraulic conductivity for these three classes. The second approach subdivided the lithologies into five classes: boulders, gravel, sand, silt, and clay. Again, a best fit hydraulic conductivity was sought for each class. Neither approach produced satisfactory results. Subdividing further to calibrate many different layers was not supported based on these initial tests. The results from the second approach are discussed to illustrate the problems encountered.

A linear model was proposed to correlate five lithology classes: boulders, gravel, sand, silt, and clay to the reported transmissvity in the P-1 database. The best fit coefficients for the five classes produced a fit with an adjusted R^2 of 0.12. Reasons for this lack of fit are illustrated by Figures 8.3.1 and 8.3.2.

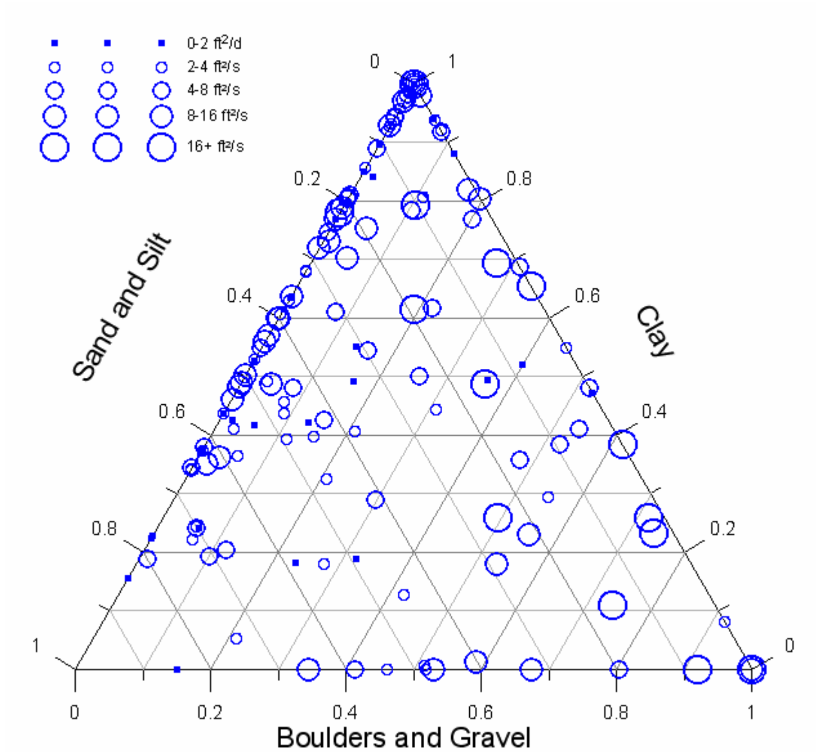


Figure 8.3.1. Reported Transmissivity from Type I Public Water Supply database and texture triangle based on reported lithology in *Wellogic* database. Transmissivity is proportional to the symbol size and given in feet squared per second.

The reported transmissivities are plotted on a texture triangle in Figure 8.3.1. The textures required to locate each point on the Figure were estimated by relating the lithology reported in *Wellogic* to the textural description. The distribution of transmissivities indicates the inherent problem trying to relate transmissivity to texture. High transmissivity is reported for all areas of the texture triangle, even wells with high percentage of silt and clay. Low transmissivity values are plotted on the triangle for wells with 60 to 80 percent sand. There is room for interpretation on the relation between lithology and texture percentages; but, there does not seem to be a way to modify the percentages used for the analysis to produce a transmissivity distribution that corresponds better to the texture triangle and shows high transmissivity values for well records with high percentages of gravel or sand and low transmissivity values for well records with high silt and clay percentage.

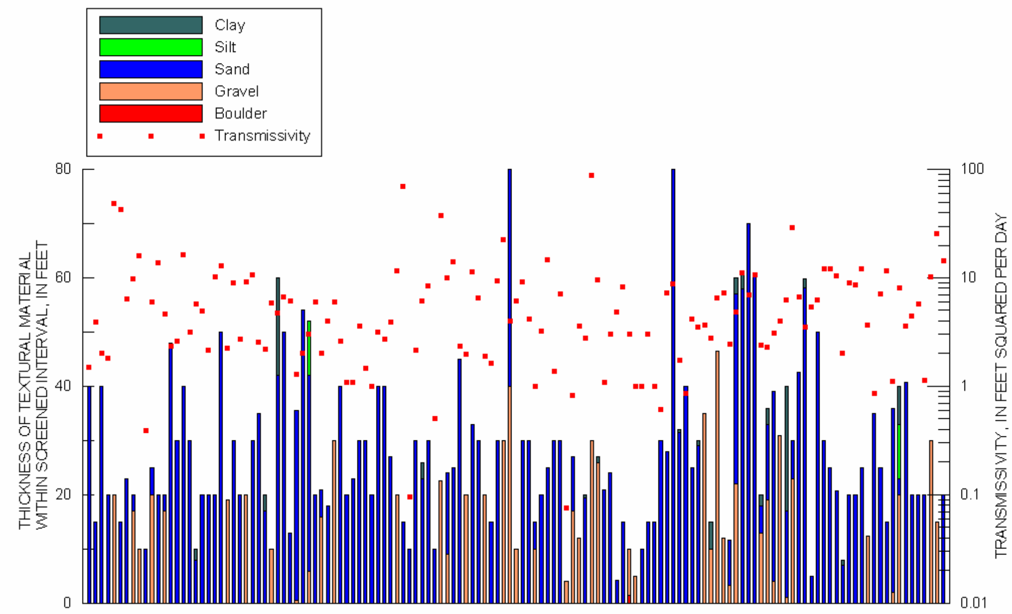


Figure 8.3.2. Reported thicknesses for five lithology classes in feet for wells in Type I Public Water Supply database and corresponding reported transmissivity in feet squared per day. Note lack of correspondence between thicknesses of various material types and reported transmissivity of wells.

The thickness reported for the five broad lithology classes and the corresponding transmissivity are plotted as Figure 8.3.2. The lack of correspondence between the reported transmissivity and reported lithology is clear in this Figure. Some of the wells with the thickest sand and gravel layers have low to modest reported transmissivities. Wells with the highest transmissivities are often in gravel layers with low to moderate thickness. One reason for this inconsistency is variation in the quality of well records. Another, and more problematic, reason for the inconsistency is that the reported lithology at the well may not control the hydraulic behavior of a well. For example, a well screened to an isolated gravel lens in a low permeability matrix may have low transmissivity due to low storage in the gravel and low hydraulic conductivity of surrounding material. A test in a similar isolated lens in a higher permeability surrounding material, however, may have much higher transmissivity since the surrounding material provides storage and can readily supply water to the lens. The size of the conductive lens also is important. An adequate domestic supply may be derived from a rather limited sand or gravel lens that would not provide adequate storage for a high-capacity well.

A final issue that confounds the use of the P-1 database for correlation of lithology to transmissivity is that the P-1 database is probably subject to exploration bias. Type I Public Water Supply Wells will tend to be in glacial deposits that yield sufficient water for the owner. In areas of the State where glacial deposits only have low or modest yield, the Public Water Supply wells may be locally the highest capacity wells. In addition, the focus of the aquifer test analysis or the well head protection analysis is local well properties, not observation well response or late-time response of the system. The water supply analysis is designed to estimate the yield for the production well, and, in some cases, the analysis may overestimate the regional transmissivity applicable to more distant observation wells.

Direct linear correlation between lithology and transmissivity values from the P-1 or RASA databases did not give satisfactory results. Other options to use lithology to estimate transmissivity are explored in the following sections. The exploration bias present in the aquifer-test databases, however, suggests that these values should be used to guide the estimates and not as firm calibration targets. The limitations of these databases have to be recognized when evaluating the performance of the estimation techniques.

8.4 Yield Estimation Using Specific Capacity Data

Water well records also may report the results of test pumping the well to demonstrate it has sufficient yield for the purpose drilled, and the information can be used to estimate the specific capacity of the well. The use of specific capacity to estimate aquifer yield was investigated by relating specific capacity to transmissivity.

The specific capacity of a well is the yield of the well in volume per time per unit of drawdown (Driscoll, 1986). In addition to characterizing the performance of a well, specific capacity values reported on water well records may be used to estimate the transmissivity of the aquifer near the well. Two factors complicate the use of specific capacity information from *Wellogic* to characterize the glacial aquifers in the State: 1) only about ten percent of the well records have appropriate specific capacity information, and 2) correlation between specific capacity estimates of transmissivity and the transmissivity determined through analysis of traditional aquifer tests typically is poor (Bradbury and Rothschild, 1985; Razack and Huntley, 1991; Hughson and others, 1996; Christensen, 1995a, 1995b).

The simplest relation between specific capacity and transmissivity is obtained by considering the Theis solution describing drawdown in an infinite confined aquifer (Freeze and Cherry, 1979),

$$s(r) = \frac{Q}{4\pi T} W(u) \tag{8.4.1}$$

Where, $s(r)$ is the drawdown at a radial distance r from the pumping well, Q is the pumping rate, T is aquifer transmissivity, $W(u)$ is the well function in which u is a dimensionless term that depends on aquifer characteristics, the radial distance, and time. Rearranging to arrive at an expression for transmissivity and to isolate specific capacity

(Q/s_w), explicitly writing the equation for drawdown at the pumping well, and including the definition of u yields,

$$T = \left[\frac{Q}{s_w}\right]\frac{1}{4\pi}W\left(\frac{Sr_w^2}{4Tt}\right) \tag{8.4.2}$$

Where s_w is the drawdown at the pumping well, r_w is the radius of the pumping well, t is time since pumping started, and S is the aquifer storativity. Equation (5) is non-linear in transmissivity because it appears in the well function. Numerical testing has revealed, however, that if the specific capacity is provided, then a simple iterative approach can be used to determine transmissivity.

To use equation 8.4.2 to calculate aquifer transmissivity, aquifer storativity, radius of the pumping well, drawdown at the pumping well at a given time, and discharge from the well must be provided. Aquifer storativity is generally not known. Fortunately, storativity does not vary over a large range once the aquifer is determined to be either confined or unconfined, and, because this term appears in the well function, transmissivity is not a strong function of storativity. If the well is known to be confined or unconfined, a reasonable guess for storativity can be made to yield a reasonable approximation of transmissivity. Water-well records typically report the results of test pumping the well, and the information requested on the *Wellogic* form includes test duration, test pumping rate, drawdown at the well, well diameter, and test type. Many records do not include all of this information. A larger problem for the use of this information to estimate transmissivity using the *Wellogic* data, however, is the type of test performed and the associated information that is reported on the record.

Many tests reported on the water well records were performed using air-lift pumping, and, under most conditions, this test does not provide the drawdown required to estimate the transmissivity of the aquifer adjacent to the well. To perform an air-lift test, the driller lowers an air line into the well below the water level in the well and introduces air to the casing. The addition of air below the water surface forms an air-water mixture above the air line that is less dense than the water in the well. This less dense mixture rises in the well casing. Air is continuously added such that the air-water mixture rises to the surface where the flow of water is measured. Flow is continued for a given time to allow the flow rate to stablize, typically an hour or two, and the final flow rate reported (Driscoll, 1986). This type of test is adequate to show that the well produces sufficient water for domestic use. Unfortunately, the depth of submergence of the air line below the initial water level typically is reported, and this depth is not the required drawdown distance necessary to determine the specified flow rate and thus provide a reasonable estimate of specific capacity.

For large diameter wells, a smaller diameter pipe, referred to as an educator, may be put into the well to increase the efficiency of the air-lift pump (Driscoll, 1986). The air line is put into the educator pipe, and water is lifted in the manner described in this smaller pipe. If the driller measures the water level in the annular space between the well casing and the educator pipe, the appropriate drawdown for use in the specific capacity analysis is obtained. Unfortunately, there is no way to automatically screen the tens of thousands well records reported as air lift to ascertain whether the test depth reported is the depth of the air line or the depth to the water level in the annular space. Because of the problems inherent with most yield tests provided in the *Wellogic* database, only tests that were performed using bailer, plunger or test pump were considered in the following analysis. The total number of useable specific capacity tests available from *Wellogic* was

20,764, and, of the total, 36 were for public water supply wells that also had an aquifer-test transmissivity value.

Two approaches to correlate aquifer transmissivity to specific capacity were tested. The first is an extension of the Theis solution given in equation (4) to include the effects of partial penetration of the pumping well and well efficiency (Bradbury and Rothschild, 1985). In this approach, the well function in equation 8.4.) is approximated by a series solution (Cooper and Jacob approach, Freeze and Cherry, 1979), a term accounting for well loss, s_l, is included, and a term to account for partial penetration of the well (screening the well to less than the entire thickness of the aquifer), s_p, is added (Bradbury and Rothschild, 1985):

$$(s_w - s_l) = \frac{Q}{4\pi T}\left[\ln\left(\frac{2.25Tt}{Sr_w^2}\right) + 2s_p\right] \tag{8.4.3}$$

s_w is the observed drawdown, and s_l is a correction for well losses to account for well efficiency defined as

$$s_l = CQ^2 \tag{8.4.4}$$

C is the well loss coefficient. The partial penetration factor is given by,

$$s_p = \frac{1-\frac{L}{B}}{\frac{L}{B}}\left(\ln\left(\frac{B}{r_w}\right) - G\left(\frac{L}{B}\right)\right) \tag{8.4.5}$$

Where L is the distance the well penetrates the aquifer, B is the thickness of the aquifer, and

$$G\left(\frac{L}{B}\right) = 2.948 - 7.363\left(\frac{L}{B}\right) + 11.447\left(\frac{L}{B}\right)^2 - 4.675\left(\frac{L}{B}\right)^3 \qquad (8.4.6)$$

Isolating specific capacity and writing the equation for transmissivity yields,

$$T = \left[\frac{Q}{(s_w - s_l)}\right]\frac{1}{4\pi}\left[\ln\left(\frac{2.25Tt}{Sr_w^2}\right) + 2s_p\right] \qquad (8.4.7)$$

Equation 8.4.7 was used to test the relation between specific capacity and aquifer transmissivity for the 36 wells with both specific capacity and aquifer-test transmissivity values. The non-linear equation was solved by successive substitution using a simple FORTRAN code. The well loss coefficient is unknown, and UCODE (Poeter and Hill, 1998) was used to find the value of *C* that produced the best fit between the aquifer-test transmissivity and that computed using equation 8.4.7. The best match between the aquifer-test transmissivity and specific capacity estimate is shown in Figure 8.4.1. The *C* value that produced this match was 2.6 sec^2/ft^5. This value is consistent with negligible clogging or well deterioration for the wells in this set (Walton, 1991). The R^2 of the fit was 0.323, and while the values are fairly well distributed around the 1:1 line, the slope of the best fit line to the relation was 0.377. If the specific-capacity-derived transmissivity values matched the aquifer-test-derived values of transmissivity then the slope would be one. Two points that had low specific-capacity-derived transmissivities and high aquifer-test transmissivities appeared to have a large impact on this fit. If these two points (circled on the figure) are dropped, the R^2 improves to 0.518 and the slope increases to 0.60. These fits are consistent with, and slightly better than, those reported in the literature (Razack and Huntley, 1991; Hughson and others, 1996; Christensen, 1995a, 1995b).

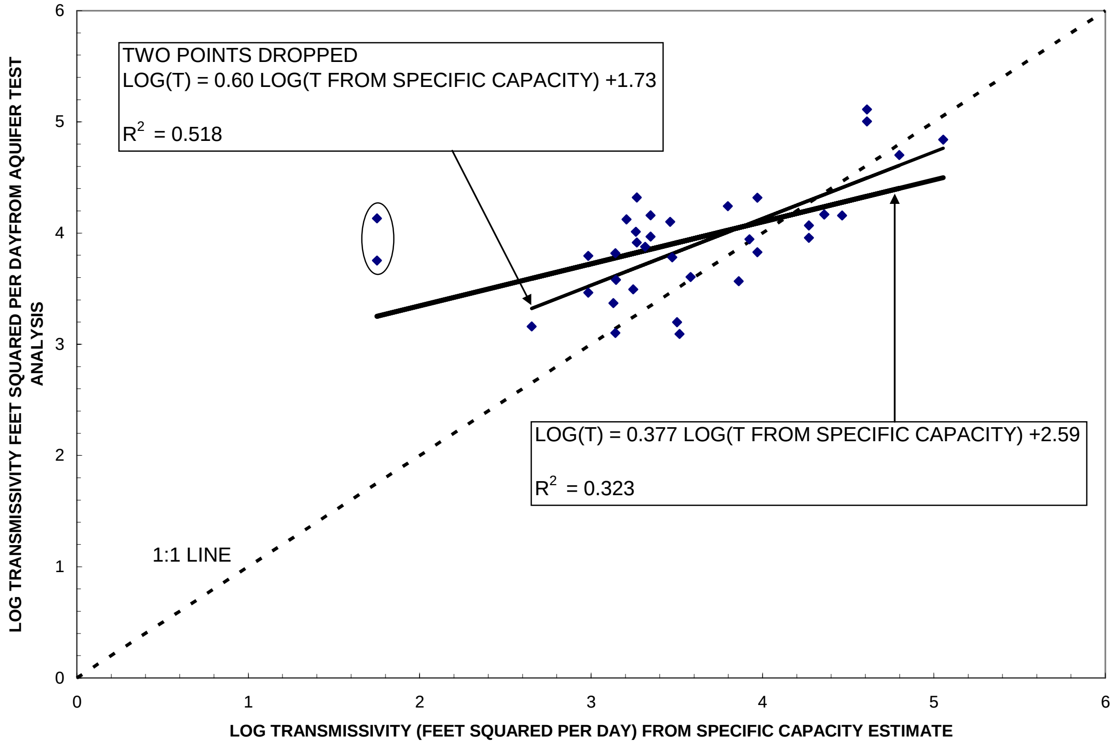


Figure 8.4.1. Relation between aquifer-test log(transmissivity in feet squared per day) and log(transmissivity in feet squared per day) estimated from specific capacity with information from *Wellogic* database for wells in the P-1 database using the Bradbury and Rothschild (1985) extension of the Theis equation accounting for partial penetration and well losses.

The second approach to relating specific capacity to transmissivity is a simple log-log correlation (Razack and Huntley, 1991; Christensen, 1995a, 1995b). This empirical relation was suggested by Razack and Huntley (1991) because of the lack of fit between the theoretical equation (such as equation 8.4.7) and values for a dataset in Morocco. Christensen (1995a) shows that this relation can be derived from the Cooper-Jacob equation with appropriate assumptions. Christensen (1995a) proposes,

$$\log(T) = \beta \log\left(\frac{Q}{s}\right) + \beta_0 \qquad (8.4.8)$$

β_0 is a constant that depends on test conditions, measurement errors, and well efficiency. The coefficient β is related to well efficiency. If β is close to 1.0, the well efficiency for the set of observations is either constant or a random variable that is uncorrelated with specific capacity. If β is significantly different than 1.0, the specific capacity and well efficiency are correlated. Equation 8.4.8 was used to fit the data from the 36 wells with both specific capacity and aquifer-test transmissivity values as shown in Figure 8.4.2. The R^2 for the fit was 0.474, which is consistent with other values reported in the literature using the same method. Note that β is 0.51 implying that well efficiency and specific yield are correlated for the dataset analyzed.

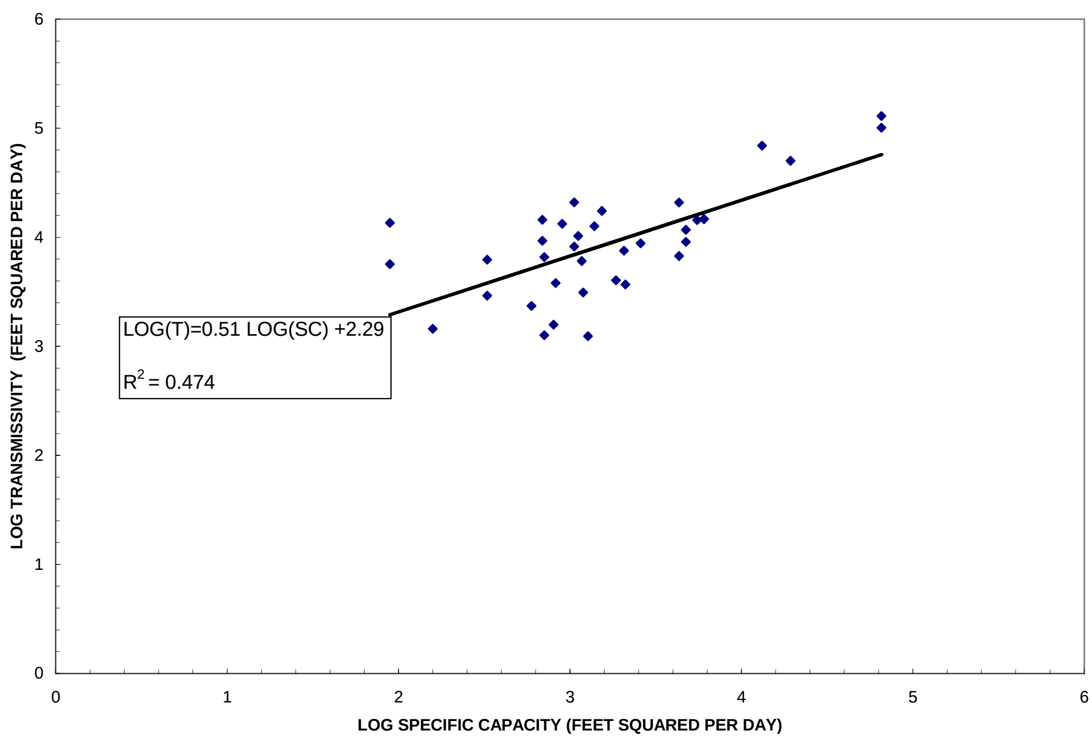


Figure 8.4.2. Relation between log(transmissivity in feet squared per day) and log(specific capacity in feet squared per day) from the P-1 and *Wellogic* databases.

Given the best fit value for the well loss coefficient, *C,* for application of equation (10) and the best-fit coefficients for the log-log correlation (equation 8.4.8), the aquifer transmissivity was estimated for the 20,764 wells with appropriate specific capacity information in the *Wellogic* database. A representative map generated with the log-log correlation is presented in Figure 8.4.3. The major problem with this method for developing statewide estimates is the poor coverage for well records with information required to make specific capacity estimates. Some general trends evident in the Drift Index or equivalent hydraulic conductivity maps can also be identified on Figure 8.4.3. With either estimation technique, the specific capacities reported for the eastern portion of the Lower Peninsula south of Saginaw Bay produce transmissivity estimates that are lower than those reported for other areas of the state. On Figure 8.4.3, which shows log(transmissivity) estimates, the estimates southeast of Saginaw Bay are an order of magnitude or more lower than other areas of the State. Southwest Michigan and portions of the northern Lower Peninsula have the highest estimated transmissivities.

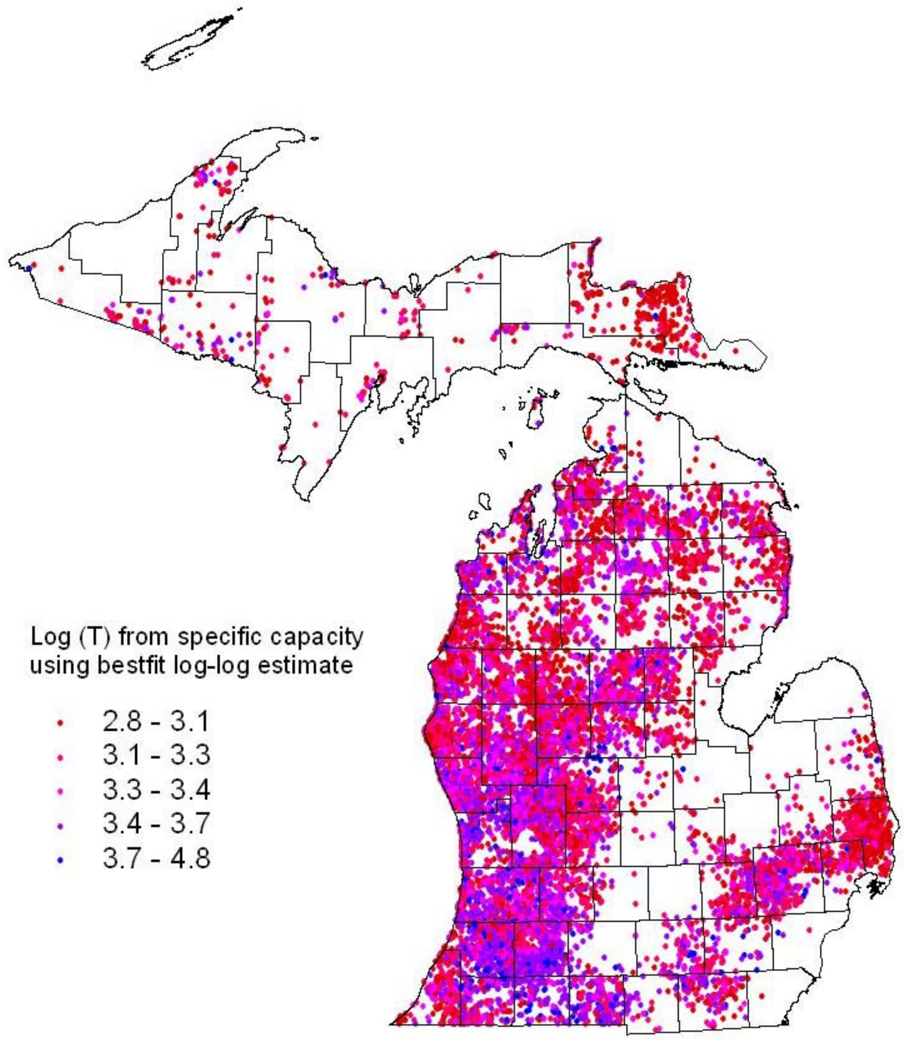


Figure 8.4.3. Estimated log(transmissivity) using information from *Wellogic* database and log-log relation between specific capacity and transmissivity derived from P-1 and *Wellogic* databases.

8.5 SAS Clustering Based on *Wellogic* Data

The previous approaches attempted to characterize the aquifer properties by examining the individual water-well records in the *Wellogic* database and identifying the spatial patterns revealed in the analysis. An alternate approach is to attempt to statistically cluster the individual water-well records in the database and then determine the hydrogeologic characteristics for each cluster. The clustering approach was tested in an attempt to remove some of the confounding scatter in the estimates made using individual water-well records and allow the analysis to focus on the general behavior predicted for statistically similar areas in the State.

From the *Wellogic* database, much information is available to characterize the geologic materials encountered during drilling and to describe the well location relative to the geologic setting within the State. Multivariate analysis methods can be used to simultaneously analyze the multiple measurements available for a number of wells. The multivariate analysis methods used during this study included factor analysis, cluster analysis, and discriminant analysis. Factor analysis allows appropriate variables for subsequent cluster analysis to be identified. Factor analysis is one class of multivariate methods whose primary purpose is data reduction and summarization (Hair and others, 1987, p. 235). The interrelationships among a large number of variables are analyzed allowing the variables to be explained in terms of their common underlying dimensions. After the initial solution has been derived, additional solutions are performed with the number of extracted factors increased and decreased from the initial solution so that the final number of factors can be chosen to best represent the original data. With this technique, the information contained in a number of original variables is condensed into a smaller set of new factors or components. Variables with the highest factor loading are selected to represent each factor and can then be used in subsequent analyses.

Cluster analysis is a technique for grouping individuals or objects into clusters so that objects in the same cluster are more like each other than they are like objects in other clusters (Hair and others, 1987, p. 293). Cluster analysis permits a large number of objects to be reduced to smaller subgroups according to natural relationships. Thus, wells with similar characteristics can be identified. The information from an entire population or data set can be reduced to information about specific smaller subgroups (Hair and others, 1987, p. 296). The characteristics, for example, transmissivity or hydraulic conductivity, of the smaller subgroups can then be compared to determine differences and similarities among groups.

After identification of appropriate variables for cluster analysis and the development of clusters, the hydrogeologic characteristics among clusters can be compared. For each cluster of wells, an effective hydraulic conductivity or transmissivity was determined based on aquifer test results or hydraulic properties of materials described during well installation. These values were compared using the analysis of variance (ANOVA) statistical technique. This technique is used to determine if samples come from populations with equal means; in other words, do wells within a cluster have similar transmissivities that differ from the transmissivities of wells in other clusters.

A final statistical technique used during this study to classify wells was discriminant analysis. Discriminant analysis requires prior knowledge of the groups, usually from a sample of objects for each group; whereas the purpose of cluster analysis is to construct a classification. Discriminant analysis is appropriate for problems that involve a categorical dependent variable, such as a cluster, and several metric independent variables, such as those derived from well information. Discriminant analysis involves deriving the linear combination of the two or more independent variables that will discriminate best between the defined groups (Hair, 1987, p. 75). This analysis establishes a procedure to classify objects into groups on the basis of their scores on several variables. Therefore, the discriminant function derived using variables from one data set can be used to classify data using the same variables from another data set.

For example, in this study wells with aquifer test information were classified and the resulting discriminant function used to classify wells without aquifer test information.

Various starting data sets of the water-well record information were analyzed using the multivariate methods in order to characterize the hydrogeological properties of the glacial drift. Data sets included wells from one county or from the whole Lower Peninsula of Michigan. Other data sets included wells installed by well drillers who have drilled more than 1,000 wells in the Lower Peninsula or wells with aquifer test information. Several randomly drawn subsets of wells from the Lower Peninsula were selected to determine whether cluster analysis would produce similar clusters from the different data sets. Most data sets were further separated into smaller groups based on whether the wells were in confined or unconfined aquifers. On the basis of factor analysis, various sets of variables describing wells within these groups were selected for cluster analysis. These variables included the elevation of the midpoint of the well screen, the percent of drift explained (or drilled through) by the well, well depth, elevation of the land surface at the well location, thickness of aquifer material near the well screen, total glacial drift thickness at the well location, the ratio of aquifer to confining unit material in the drift, the percent aquifer material in the aquifer and in the drift, the percent marginal aquifer material in the aquifer and in the drift, static water level elevation, estimated vertical and horizontal hydraulic conductivity, specific capacity, and well location. An additional variable, called the Drift Index (Section 4.2.1.1), was computed from the percents of aquifer, marginal aquifer, partially confining unit, and confining unit materials for the well. This drift index variable and an existing categorical variable describing the land-system geologic features at each well location were used in separate analyses as the classification variable in conjunction with available well information to determine the discriminant function. This analysis was meant to investigate whether wells were hydrologically similar in the different drift index or land-system groups. In other words, would the selected variables produce a function in which almost all wells were reclassified into their original group? All variables were standardized before analysis because the variables have different units and because the ranges of some variables, such as well location, were much larger than the ranges for other variables. For each cluster analysis performed, generally four to five of the above variables were used in the analysis. Also for each analysis, multiple numbers of clusters were calculated and plotted to determine relative positions within the State and to known hydrogeological features. After cluster analysis with data sets comprised of wells with aquifer test information, differences among transmssivities in clusters were investigated using the analysis of variance method.

Transmissivities of clusters based on wells with aquifer test information were generally not significantly different among clusters indicating that the clusters did not describe much of the variability of the glacial deposits. Since wells with aquifer test information were generally municipal wells which are drilled in highly productive aquifer materials that are often not representative of surrounding well materials, this result of low significance is not unexpected. The number and extents of clusters derived from different data sets generally varied, again indicating that the analysis was not consistently describing the variability in the glacial deposits. When groups determined using cluster analysis or from existing categorical variables were subsequently reclassified using discriminant analysis, many wells were reclassified into different groups. Also reclassification of data sets comprised of wells without aquifer test information using the discriminant function derived using variables from wells with aquifer test information did not result in hydrogeologically similar clusters. The fact that cluster analysis and discriminant analysis did not result in clusters that explained the variability in the glacial drift deposits underscores the extreme variability of the glacial deposits. Often nearby wells contain different descriptions for the type and thickness of the subsurface materials and the characteristics of the glacial drift materials also vary statewide. The type of glacial material that constitutes an aquifer in one part of the state may not be an aquifer in another part of the state. There are possibly other important variables that describe the properties of the glacial materials at each well location that, if included in the statistical analysis, would have resulted in hydrogeologically similar clusters or would have made possible the assignment of aquifer transmissivities from wells with aquifer tests to wells with unknown aquifer properties. A different partitioning of wells into data sets based on other drift characteristics than those used for this study may also have resulted in better characterization of the glacial-drift materials.

8.6 Non-Linear Regression Techniques

The lack of success with linear regression using either lithology directly or using equivalent hydraulic conductivity as in intermediate step was disconcerting since lithology and aquifer characteristics are thought strongly related. Non-linear regression techniques were used to determine if these methods allowed lithology or equivalent hydraulic conductivity to be related to the reported aquifer transmissivity in the public water supply database. This method does not address inconsistencies between drillers in the same area of the State or the exploration bias found in the public water supply database. It does, however, allow provide other approaches to evaluate the data and discover if a relation between lithology, Drift Index, or specific capacity and transmissivity can be identified. After a review and preliminary testing of a variety of methods, only the artificial neural network approach seemed promising.

Artificial Neural Networks (ANNs) include a wide variety of statistical models that can represent diverse situations configurable in a network architecture. A feed forward ANN uses an input vector to propagate a signal through a series of two or more model layers and produces one or more outputs. Back propagation is technique for systematically adjusting the parameters of a feed forward network to predict quantities of interest. In this application, back propagation was used to train a feed forward network to estimate measured transmissivities and computed effective conductivities as target variables using well properties and geologic characteristics as input variables.

The ANN construct is based on biological neural networks, like the brain, and shares some of its nomenclature. Thus, an artificial neuron is a function that is the basic building block of an ANN. Similar to a multiple regression equation, an ANN neuron multiplies an input vector of length R, by a corresponding set of weights w and adds a bias factor b, which functions like an intercept term.

In contrast to a multiple regression equation, however, the output n receives additional processing by the operation of a transfer function. Transfer functions used in feed forward networks commonly are differentiable functions that have no parameters. In this report, tan-sigmoid transfer functions (Demuth and Beale, 2004) were used in internal (hidden) model layers and a linear transfer functions was used in the output layer. The tan-sigmoid function is a monotonically increasing function that maps all inputs to outputs in the range from negative to positive one. A linear transfer function maps input identically to output. To develop these models, common logarithms (log) were computed for the field transmissivity values, which were originally expressed in feet squared per minute. Then both log transmissivity values and input variables were rescaled to range between negative one and positive one prior to network training. Outputs from the model were inversely scaled to correspond with the original units of measurements.

Artificial neurons are arranged in layers within a feed forward network. In the first model layer, each neuron receives data from every element in the input vector. In subsequent model layers, each neuron receives input data from every transfer function in the previous model layer. The number of neurons in the final model layer matches the number of output variables. Commonly, neurons in the first and middle layers contain sigmoid transfer functions, while neurons in the final layer are linear transfer functions so that the range of output values is not constrained.

Multiple layer networks are quite powerful. A network with only two layers, and perhaps a large number of neurons, can be developed to estimate any function (with a finite number of discontinuities) arbitrarily well (Demuth and Beale, 2004, p. 2-12). Multiple layer networks have the flexibility to identify linear and nonlinear relations among input and output variables (Demuth and Beale, 2004, p. 5-6). These networks also may have a large number of parameters.

Like other statistical models, ANNs are developed by optimizing parameters associated within a specified model structure. The optimization process, referred to as training, systematically adjusts the parameters of weights and biases to predict one or more target variables based on the corresponding input variables. In ANNs with large numbers of parameters relative to the number of observations, the model may over fit the measurements, and not predict new observations with the precision indicated by the set of measurements used in training. In this analysis, a performance function was selected to penalize over parameterization.

The performance function of a statistical model is commonly defined by the mean square error (*mse*), which is the sum of squared differences between measured and estimated values, divided by the number of measurements (Demuth and Beale, 2004, p. 5-52). To improve prediction accuracy, however, the performance function was modified from the *mse* to the mean square error for regression (*msereg).* This performance function weights the *mse* by a coefficient *gamma* with the quantity of one minus *gamma* times the sum of squares of the model weights and biases. The value of gamma, which is restricted to the range from zero to one, was determined by use of a Bayesian framework as implemented in the optimization function *trainbr* (Demuth and Beale, 2004, p. 5-53).

Estimation of measured transmissivity. Transmissivity is a hydraulic property of an aquifer that describes it ability to transmit water as a product of its saturated thickness and hydraulic conductivity. In this analysis, 222 field-measured values of transmissivity were the target variables and the easting, northing, and elevation of the well, the length of the well, and information on the hydraulic conductivities were input vectors. Specifically, lithologic descriptions from well-driller records were ranked to correspond to hydraulic conductivity. The layers described by the driller's record were subdivided into 25 two-foot intervals, starting at the bottom of the well. Thus, in order of appearance, the input vector contained 29 elements, 3 location variables, length of the well, and 25 ranks of hydraulic conductivity.

To avoid over parameterizing the feed forward network with a limited number of transmissivity measurements, weights and biases were repetitively estimated using a random permutation of 172 transmissivity measurements and corresponding input vectors as the training set. After training, transmissivities were estimated at the remaining 50 wells for validation. For each training event in which optimization was successful, a mean square error was computed for the training set to reflect estimation accuracy, and for the validation set to indicate prediction accuracy.

Several feed forward model structures were developed and assessed. One of the structures considered successful contained three layers. The first (input) layer contained three tan-sigmoid neurons, the second layer contained one tan-sigmoid neuron, and the output layer contained one linear neuron. For this structure, the distribution of mean square errors for estimation was only somewhat larger than corresponding mean square errors for prediction (Figure 8.6.1).

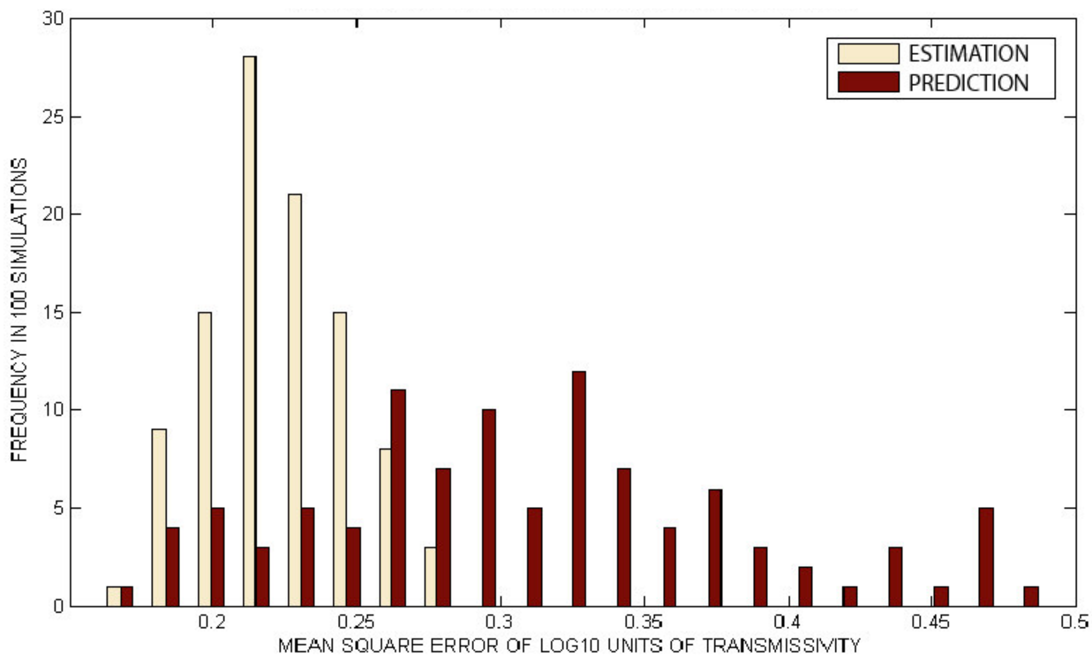


Figure 8.6.1. Distribution of estimation and prediction mean square errors for the selected feed forward neural network

In this analysis, estimation and prediction mean square errors were inversely related (Figure 8.6.2). The inverse relation is thought to result from the variability of measurements making up the individual training and validation sets, rather than indicating that estimation and prediction mean square errors would, in general, be inversely related. Estimation mean square error also was inversely related to the correlation between estimated and measured values (Figure 8.6.3).

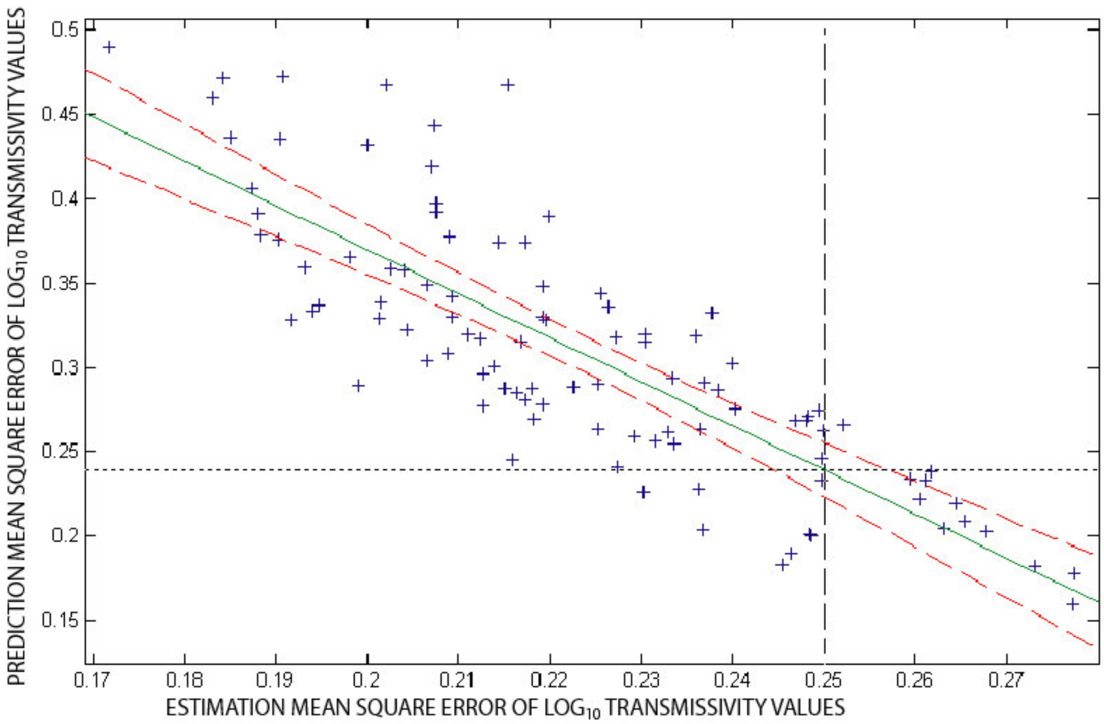


Figure 8.6.2. Inverse relation between estimation and prediction mean square errors

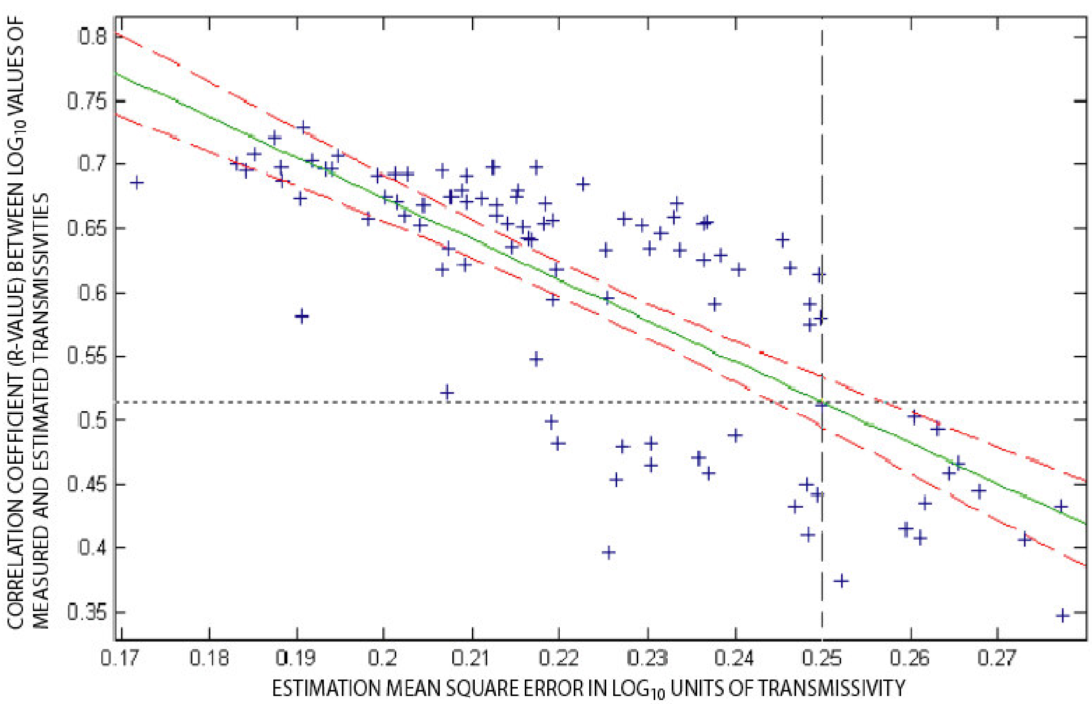


Figure 8.6.3. Inverse relation between estimation mean square error and correlation coefficient between estimated and predicted $\log_{10}$ transmissivity values

A multiple regression equation was developed to compare with results obtained using the feed forward neural network. The regression equation contained the same 29-element input vector provided to the neural network, and was augmented with a one for comparability with the bias element in the feed forward network. The resulting model correlation coefficient of 0.459, was slightly less than the neural network, although the estimation mean square error of 0.253 was comparable. Only the length of well variable, number 4, indicated statistical significance at the 5 percent level (Figure 8.6.4).

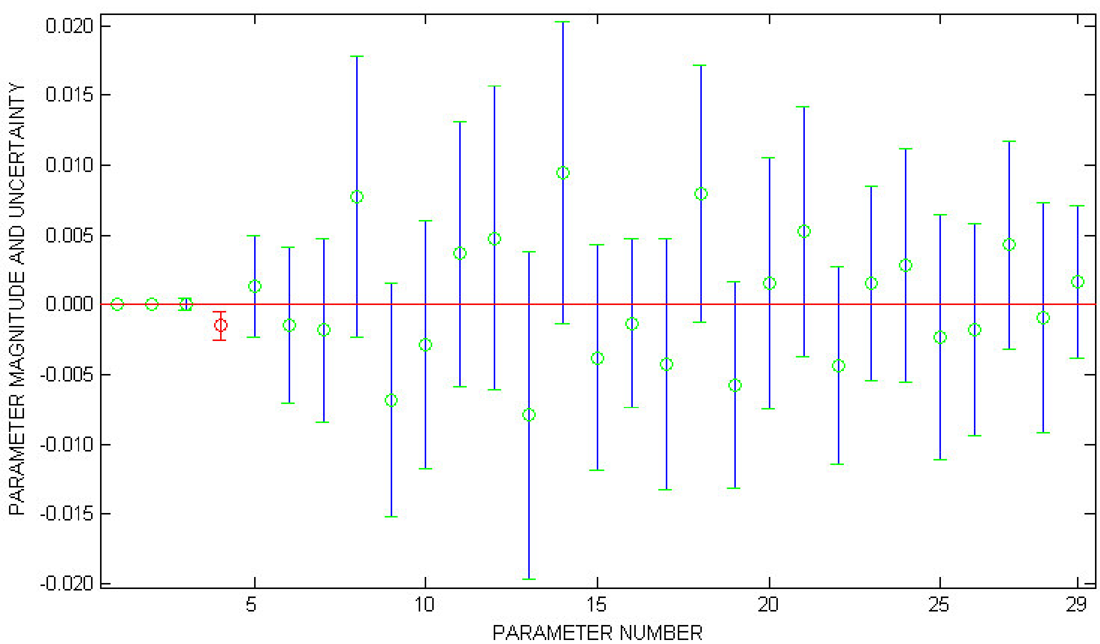


Figure 8.6.4. Multiple regression coefficient magnitudes and uncertainties

Estimation of computed effective hydraulic conductivity. In this analysis, hydraulic conductivities were computed on the basis of lithologies described by drillers records, and common values of hydraulic conductivities associated with idealized lithologies. Effective hydraulic conductivities were computed by weighting the estimated hydraulic conductivities by the saturated thicknesses of the lithologies described in the well record.

Both horizontal and vertical effective hydraulic conductivities were computed. A common logarithmic transform was used to help normalize the distribution of effective hydraulic conductivities prior to estimation.

The distribution of log hydraulic conductivities varied significantly depending on the set of wells used in developing the estimates, the number of lithologic categories used in describing the distribution, and whether the uncertainties of hydraulic conductivities for individual lithologies were considered. In the simplest case where only three lithologies of clay, sand, and gravel were considered, the distribution of log hydraulic conductivities at more than 271,000 wells located across the state, showed three distinct peaks (Figure 8.6.5). Although this distribution of hydraulic conductivities may over simplify the actual distribution of hydraulic conductivities, the data were considered adequate for preliminary assessment of a neural net model.

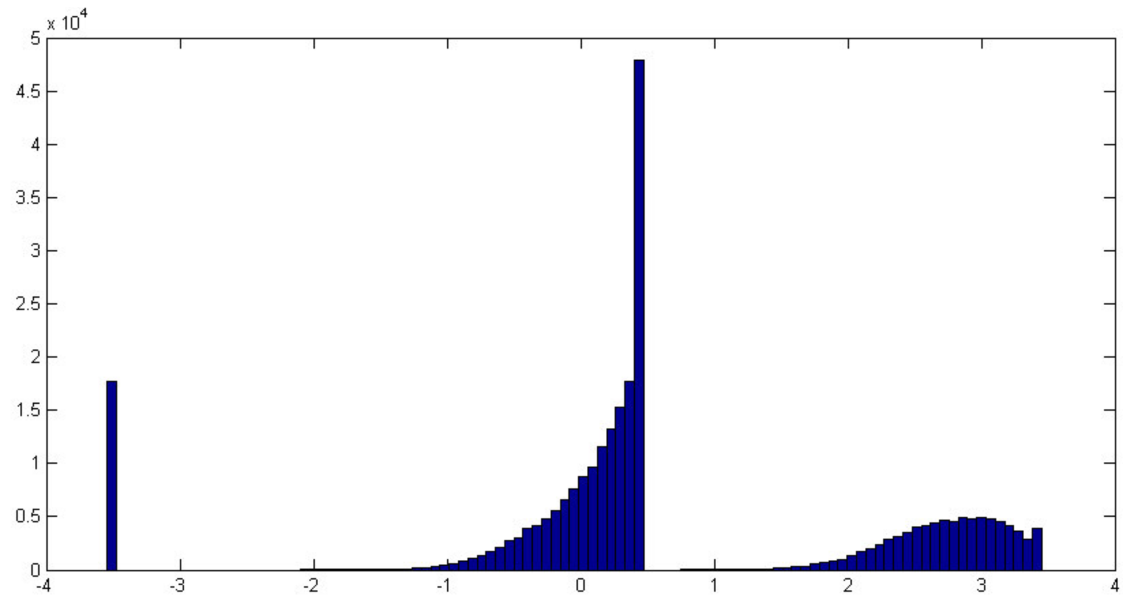


Figure 8.6.5. Distribution of effective horizontal hydraulic conductivities computed on the basis of three idealized lithologies available from 271,000 wells statewide

A three-layer feed forward neural network model was defined to estimate the computed effective horizontal hydraulic conductivities. The first and second layers contained 10 tan-sigmoid neurons, and the output layer contained one linear neuron. The input vector contained the easting and northing coordinates of the well and the total clay, sand, and gravel thicknesses in the saturated zone described by the well records. Training was terminated after the correlation coefficient between model estimates and computed hydraulic conductivities equaled one to two significant digits. It is assumed that simplifications in the model structure and input vector would be possible while maintaining a high correlation. A multiple regression model using the same input vector and target variable resulted in a linear correlation coefficient of only 0.62.
Further development of the model was not considered warranted, however, because the correlation between computed and actual effective hydraulic conductivities is uncertain. Because of the large number of measurements available, a more refined description of the distribution of effective hydraulic conductivities derived from more lithologic categories could likely be predicted accurately with an appropriately parameterized feed forward model. Including uncertainties in the hydraulic conductivities of idealized lithologic units would likely produce a more realistic distribution of effective hydraulic conductivities at wells, but would be more difficult to predict exactly because of the randomness necessarily introduced in the computation.

In summary, the utility of feed forward neural networks for predicting aquifer properties appears to be limited by the number of measurements of aquifer properties. Limited numbers of measured transmissivity values limits the structure of feed forward models and their potential for identifying nonlinear relations between the input vectors and the target variables. Neural networks, however, were shown to have greater accuracy than multiple regression equations when large numbers of observations were available.

8.7 Depth to Water Table in SSURGO-2 Soils

Query for the depth to the water table (in feet) for each Mapping Unit. The water table can be in the solum (top 6 - 7 ft) during any month.

From Cosoilmoist table

Top Depth – High Value (soilmoistdept_h)
Bottom Depth – Low Value (soilmoistdepb_l) = 183
Soil moisture (soimoiststat) = Wet
comonthkey

From Mapunit table

muname
mukey
musym

From Component table

major component key (majcompflag) = Yes
component percent (compct_r) [reprehensive value]

From Comonth table

cokey – which relates to the comonth key in Cosoilmoist table

In the Access database (using the NRCS template), run the report **MANU – Table K1 Water Features** with all values selected. Run the following select query (**muWT183W_Q**).

SELECT comonth.cokey, comonth.comonthkey, mapunit.muname, mapunit.musym, mapunit.mukey, component.compname, component.comppct_r, [Subreport - Table K1 - Water Features - Water Table].soimoistdept_h, component.majcompflag, cosoilmoist.soimoistdepb_l, cosoilmoist.soimoiststat INTO muWT183WetMajComp FROM mapunit INNER JOIN ((component INNER JOIN ([Subreport - Table K1 - Water Features - Water Table] INNER JOIN comonth ON [Subreport - Table K1 - Water Features - Water Table].comonthkey = comonth.comonthkey) ON component.cokey = comonth.cokey) INNER JOIN cosoilmoist ON comonth.comonthkey = cosoilmoist.comonthkey) ON mapunit.mukey = component.mukey
WHERE (((component.majcompflag)="Yes") AND ((cosoilmoist.soimoistdepb_l)=183) AND ((cosoilmoist.soimoiststat)="Wet"));

The table (muWT183WetMajComp) is produced by month – but all months are the same. Only one set of values is needed. Duplicates can be eliminated using ***cokey*** as the primary key. Resulting table**: muWT183WetMajComp_U**.

For a map unit (***mukey***) to be included, over 50% of the area must have the water table in the soil zone (6 or 7 ft). The sum of ***comppct_r*** values for each map unit must be > 50%.

Only one value of water table depth is needed. A spatially weighted value is calculated, based on the percent of the total area represented. This final value is converted from centimeters to feet.

8.8 Aquifer Designation Table from Source Water Assessment Program

Table 8.8.1 summarizes the aquifer classification (AQ, MAQ, PCM, CM) for the lithologic entries in *Wellogic*. The assessment class is based on the primary lithology and the secondary descriptor is used to modify the class based on the assessment qualifier. For the Source Water Assessment Program (Michigan Department of Environmental Quality, 2005), an assessment qualifier of "up" indicates the lithologic unit acts as a better confining unit and an assessment qualifier of "down" indicates the unit is less confining.

Table 8.8.1 Aquifer Classification Table from Source Water Assessment Program

DESCRIPTION 1 (primary color)	DESCRIPTION 2 (primary material)	ASSESSMENT CLASS	DESCRIPTION 3 (secondary descriptor)	ASSESSMENT QUALIFIER
BLACK	BASALT	MAQ	BROKEN	Down
BLACK & GRAY	BOULDERS	AQ	CEMENTED	Up
BLACK & WHITE	CLAY	CM	CLAYEY	Up
BLUE	CLAY & BOULDERS	CM	CLEAN	No Effect
BROWN	CLAY & COBBLES	CM	COARSE	No Effect
CREAM	CLAY & GRAVEL	PCM	DENSE	No Effect
DARK GRAY	CLAY & SAND	PCM	DIRTY	Up
GRAY	CLAY & SILT	PCM	DOLOMITIC	No Effect
GRAY & WHITE	CLAY & STONES	PCM	DRY	No Effect
GREEN	CLAY GRAVEL SAND	PCM	FILL	No Effect
LIGHT BROWN	CLAY GRAVEL SILT	PCM	FINE	No Effect
LIGHT GRAY	CLAY GRAVEL STONES	PCM	FINE TO COARSE	No Effect
ORANGE	CLAY SAND GRAVEL	PCM	FINE TO MEDIUM	No Effect
PINK	CLAY SAND SILT	PCM	FIRM	No Effect
RED	CLAY SILT GRAVEL	PCM	FRACTURED	Down
RUST	CLAY SILT SAND	PCM	GRAVELY	Down
TAN	COAL	PCM	GUMMY	No Effect
TAN & GRAY	COBBLES	AQ	HARD	No Effect

WHITE	CONGLOMERATE	MAQ	HEAVING/QUICK	No Effect
YELLOW	DEBRIS		KARST	Down
	DOLOMITE	MAQ	MEDIUM	No Effect
DESCRIPTION 1 (primary color)	**DESCRIPTION 2 (primary material)**	**ASSESSMENT CLASS**	**DESCRIPTION 3 (secondary descriptor)**	**ASSESSMENT QUALIFIER**
	DOLOMITE & LIMESTONE	MAQ	MEDIUM TO COARSE	No Effect
	DOLOMITE & SANDSTONE	AQ	MUDDY	Up
	DOLOMITE & SHALE	PCM	ORGANIC	No Effect
	DRY HOLE	NA	POROUS	Down
	GRANITE	MAQ	SANDY	Down
	GRAVEL	AQ	SILTY	Up
	GRAVEL & BOULDERS	AQ	SOFT	No Effect
	GRAVEL & CLAY	PCM	STICKY	No Effect
	GRAVEL & COBBLES	AQ	STONEY	No Effect
	GRAVEL & SAND	AQ	STRINGERS	No Effect
	GRAVEL & SILT	MAQ	SWELLING	No Effect
	GRAVEL & STONES	AQ	VERY COARSE	No Effect
	GRAVEL CLAY SAND	MAQ	VERY FINE	No Effect
	GRAVEL CLAY SILT	MAQ	VERY FINE-COARSE	No Effect
	GRAVEL SAND CLAY	MAQ	VERY FINE-FINE	No Effect
	GRAVEL SAND SILT	MAQ	VERY FINE-MEDIUM	No Effect
	GRAVEL SILT CLAY	MAQ	VERY HARD	No Effect
	GRAVEL SILT SAND	MAQ	W/ BOULDERS	No Effect
	GREENSTONE	MAQ	W/ CLAY	Up
	GYPSUM	PCM	W/ COAL	Up
	HARDPAN	CM	W/ COBBLES	Down
	INTERVAL NOT SAMPLED	NA	W/ DOLOMITE	No Effect
	IRON FORMATION	MAQ	W/ GRAVEL	Down
	LIMESTONE	MAQ	W/ GYPSUM	No Effect
	LIMESTONE & DOLOMITE	MAQ	W/ LIMESTONE	No Effect
	LIMESTONE & SANDSTONE	MAQ	W/ SAND	Down
	LIMESTONE & SHALE	PCM	W/ SANDSTONE	Down
	LITHOLOGY UNKNOWN	NA	W/ SHALE	Up
	LOAM	NA	W/ SILT	No Effect
	MARL	NA	W/ STONES	No Effect
	MUCK	NA	WATER BEARING	No Effect
	MUD	NA	WEATHERED	Down
	NO LITHOLOGY INFORMATION		WET/MOIST	No Effect
	NO LOG	NA	WOOD	No Effect
	PEAT	NA		
	QUARTZ	MAQ		
	QUARTZITE	MAQ		
	SAND	AQ		
	SAND & BOULDERS	AQ		
	SAND & CLAY	PCM		
	SAND & COBBLES	AQ		
	SAND & GRAVEL	AQ		
	SAND & SILT	MAQ		
	SAND & STONES	AQ		
	SAND CLAY GRAVEL	MAQ		
	SAND CLAY SILT	MAQ		
	SAND GRAVEL CLAY	MAQ		
	SAND GRAVEL SILT	MAQ		
	SAND SILT CLAY	MAQ		

	SAND SILT GRAVEL	MAQ		
	SANDSTONE	AQ		
DESCRIPTION 1 (primary color)	**DESCRIPTION 2 (primary material)**	**ASSESSMENT CLASS**	**DESCRIPTION 3 (secondary descriptor)**	**ASSESSMENT QUALIFIER**
	SANDSTONE & LIMESTONE	MAQ		
	SANDSTONE & SHALE	MAQ		
	SCHIST	MAQ		
	SEE COMMENTS	NA		
	SHALE	CM		
	SHALE & COAL	PCM		
	SHALE & LIMESTONE	PCM		
	SHALE & SANDSTONE	MAQ		
	SHALE SANDSTONE LIMESTONE	MAQ		
	SILT	MAQ		
	SILT & BOULDERS	MAQ		
	SILT & CLAY	PCM		
	SILT & COBBLES	MAQ		
	SILT & GRAVEL	MAQ		
	SILT & SAND	MAQ		
	SILT & STONES	MAQ		
	SILT CLAY GRAVEL	MAQ		
	SILT CLAY SAND	MAQ		
	SILT GRAVEL CLAY	MAQ		
	SILT GRAVEL SAND	MAQ		
	SILT SAND CLAY	MAQ		
	SILT SAND GRAVEL	MAQ		
	SLATE	CM		
	SOAPSTONE (TALC)	PCM		
	STONES	AQ		
	TOPSOIL	NA		
	UNIDENTIFIED CONSOLIDATED FM	NA		
	VOID	AQ		

CATEGORIES	**ASSESSMENT CLASSES**	**ASSESSMENT QUALIFIER**	**ASSESSMENT QUALIFIER**
Confining Material	**CM**	**Moves**	**CM = Up**
Partially Confining Material	**PCM**	**Assessment Class**	
Marginal Aquifer	**MAQ**	**Up, Down or has no**	
Aquifer	**AQ**	**No Effect**	**AQ = Down**

RULES

PCM never becomes CM

MAQ never becomes PCM

8.9 Hydraulic conductivity for each lithology by landsystem group

Table 8.9.1 Hydraulic conductivity in feet per day for lithologies reported in *Wellogic* by landsystem group.

LITHOLOGY	HYDRAULIC CONDUCTIVITY GROUP 1	HYDRAULIC CONDUCTIVITY GROUP 2	HYDRAULIC CONDUCTIVITY GROUP 3
BASALT	0.032	0.032	0.032
BOULDERS	100	100	100
CLAY	0.0001	0.0001	0.0001
CLAY&BOULDERS	0.0001	0.0001	0.0001
CLAY&COBBLES	0.0001	0.0001	0.0001
CLAY&GRAVEL	0.00032	0.001	0.001
CLAY&SAND	0.00032	0.01	0.01
CLAY&SILT	0.0001	0.0001	0.0001
CLAY&STONES	0.0001	0.001	0.001
CLAYGRAVELSAND	0.001	0.01	0.01
CLAYGRAVELSILT	0.001	0.01	0.01
CLAYGRAVELSTONES	0.001	0.01	0.01
CLAYSANDGRAVEL	0.001	0.01	0.01
CLAYSANDSILT	0.001	0.01	0.01
CLAYSILTGRAVEL	0.001	0.01	0.01
CLAYSILTSAND	0.001	0.01	0.01
COAL	0.01	0.01	0.01
COBBLES	50	100	100
CONGLOMERATE	0.001	0.001	0.001
DEBRIS	1	1	1
DOLOMITE	0.03	0.03	0.03
DOLOMITE&LIMESTONE	0.03	0.03	0.03
DOLOMITE&SANDSTONE	0.03	0.03	0.03
DOLOMITE&SHALE	0.03	0.03	0.03
DRYHOLE	999999	999999	999999
GRANITE	0.001	0.001	0.001
GRAVEL	50	100	100
GRAVEL&BOULDERS	50	100	100
GRAVEL&CLAY	0.01	0.01	0.01
GRAVEL&COBBLES	50	100	100
GRAVEL&SAND	1	50	50
GRAVEL&SILT	1	1	1
GRAVEL&STONES	50	100	100
GRAVELCLAYSAND	0.01	0.01	0.01
GRAVELCLAYSILT	0.01	0.01	0.01
GRAVELSANDCLAY	0.01	0.01	0.01

GRAVELSANDSILT	1	1	1
GRAVELSILTCLAY	0.01	0.01	0.01
GRAVELSILTSAND	0.01	0.01	0.01
GREENSTONE	0.001	0.001	0.001
GYPSUM	0.001	0.001	0.001
HARDPAN	0.001	0.001	0.001
INTERVALNOTSAMPLED	999999	999999	999999
IRONFORMATION	0.001	0.001	0.001
LIMESTONE	0.01	0.01	0.01
LIMESTONE&DOLOMITE	0.01	0.01	0.01
LIMESTONE&SANDSTONE	0.01	0.01	0.01
LIMESTONE&SHALE	0.01	0.01	0.01
LITHOLOGYUNKNOWN	999999	999999	999999
LOAM	0.1	0.1	0.1
MARL	0.1	0.1	0.1
MUCK	0.1	0.1	0.1
MUD	0.1	0.1	0.1
NOLITHOLOGYINFORMATION	999999	999999	999999
NOLOG	999999	999999	999999
OTHR	999999	999999	999999
PEAT	0.1	0.1	0.1
QUARTZ	0.0001	0.0001	0.0001
QUARTZITE	0.0001	0.0001	0.0001
SAND	1	50	50
SAND&BOULDERS	1	50	50
SAND&CLAY	0.0001	0.1	0.1
SAND&COBBLES	1	50	50
SAND&GRAVEL	1	50	50
SAND&SILT	1	1	1
SAND&STONES	1	50	50
SANDCLAYGRAVEL	0.1	0.1	0.1
SANDCLAYSILT	0.1	0.1	0.1
SANDGRAVELCLAY	0.1	0.1	0.1
SANDGRAVELSILT	0.1	0.1	0.1
SANDSILTCLAY	0.1	0.1	0.1
SANDSILTGRAVEL	0.1	0.1	0.1
SANDSTONE	0.0001	0.0001	0.0001
SANDSTONE&LIMESTONE	0.0001	0.0001	0.0001
SANDSTONE&SHALE	0.0001	0.0001	0.0001
SCHIST	0.0001	0.0001	0.0001
SEECOMMENTS	999999	999999	999999
SHALE	0.0001	0.0001	0.0001
SHALE&COAL	0.0001	0.0001	0.0001
SHALE&LIMESTONE	0.0001	0.0001	0.0001
SHALE&SANDSTONE	0.0001	0.0001	0.0001
SHALESANDSTONELIMESTONE	0.0001	0.0001	0.0001
SILT	0.1	1	1
SILT&BOULDERS	0.1	1	1
SILT&CLAY	0.0001	0.001	0.001
SILT&COBBLES	0.1	1	1

SILT&GRAVEL	0.1	1	1
SILT&SAND	0.1	1	1
SILT&STONES	0.1	1	1
SILTCLAYGRAVEL	0.1	1	1
SILTCLAYSAND	0.1	1	1
SILTGRAVELCLAY	0.1	1	1
SILTGRAVELSAND	0.1	1	1
SILTSANDCLAY	0.1	1	1
SILTSANDGRAVEL	0.1	1	1
SLATE	0.0001	0.0001	0.0001
SOAPSTONE	0.0001	0.0001	0.0001
SOAPSTONE[TALC]	0.0001	0.0001	0.0001
STONES	1	10	10
TALC	0.0001	0.0001	0.0001
TOPSOIL	0.1	1	1
UNIDENTIFIEDCONSOLIDATEDFM	999999	999999	999999
VOID	999999	999999	999999

999999 indicates that this lithology is not used in estimation procedure.

Table 8.9.2 Hydraulic conductivity groups for each landsystem

LANDSYSTEM	GROUP
COASTAL DUNES	3
ICE-CONTACT OUTWASH	3
ICE-MARGINAL TILL	2
LACUSTRINE COARSE	2
LACUSTRINE FINE	1
LODGE TILL OR FINE SUPRAGLACIAL DRIFT	2
PROGLACIAL OUTWASH	3

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8.11 Invitees and Attendees at the Project Appraisal Meeting, March 1, 2005

		Attended
Dave Lusch	GWMAP Project Team Member	Y
Steve Miller	GWMAP Project Team Member	Y
Howard Reeves	GWMAP Project Team Member	Y
Pam Hunt	GWMAP Project Team Member	Y
Joel Annable	Peerless-Midwest, Inc.	
Bob Masters	505 Apple Tree Drive	
Mike Chapman	Ionia, Michigan 48846	
	(616) 527-0050	
Mike Brennan	Malcolm Pirnie, Inc.	
Greg Foote	1500 Abbott Road	Y
Grant Gartrell	Suite 210	
Marc Wahrer	East Lansing, MI 48823	
	(517) 337-0111	
Jim Brode	Fishbeck, Thompson, Carr & Huber, Inc.	
Andrew Schwallier	4775 Campus Dr. Kalamazoo, MI 49008	
	(269) 375-3824	
Dan Whalen	Williams & Works	Y
	616-988-3535	
Mike Tuckey	DLZ Michigan, Inc. 1425 Keystone Ave Lansing, MI 48911 (517) 393-6800	Y
Joyce Dunkin	Limno-Tech, Inc.	Y
	501 Avis Drive	
	Ann Arbor, MI 48108	
	(734) 332-1200	
Elgar Brown	GWMAP Project Team Member	Y
John Esch	GWMAP Project Team Member	Y

Mike Gaber	GWMAP Project Team Member	Y
Joe Lovato	GWMAP Project Team Member	Y
Brant Fisher	GWMAP Project Team Member	Y
Kevin Kincare	GWMAP Project Team Member	Y
Jeff Spencer	GWMAP Project Team Member	
Ronald Stone	GWMAP Project Team Member	
Richard Mandle	GWMAP Project Team Member	
Kim Finkbeiner	Kalamazoo County Human Services Dept. Environmental Health 3299 Gull Road Kalamazoo, MI 49048 (269) 373-5336	
Alan Kehew Duane Hampton	Western Michigan University Department of Geosciences 1187 Rood Hall 1903 West Michigan Ave Kalamazoo, MI 49008 (269) 387-5485	Y
David Hyndman Grahame Larson	Michigan State University Department of Geological Sciences 206 Natural Science Building East Lansing, MI 48824-1115	Y
William Northcott	Michigan State University BIOSYSTEMS & AGRICULTURAL ENG. 218 FARRALL HALL EAST LANSING MI 48824-1323 517-432-7702	
Kevin Cole Patrick Colgan	Grand Valley State University, Geology Dept. Padnos Hall of Science # 125 One Campus Drive Allendale, Michigan 49401-9403 (616) 331-3728	
Jeff Stollhans	Layne Northern 3126 N. M.L. King Jr. Blvd. Lansing, MI 48906	

Dave Keller	Keller Well Drilling Inc. 5615 Chilson Howell, MI 48843	
Tim Clark	Cribley Drilling Co., Inc 8300 Dexter Trail Dexter. MI 48130	
Harry Brown	Brown Drilling Co., Inc. 7215 Highland Rd. Howell, MI 48843	
Bryan Brewer	Central Wells & Pumps 3881 E. Broadway Muskegon, MI 49444	Y
Ed Everett	Blackhawk Geophysical Services 585 Jewett Road Mason, MI 48854	Y
Michael Mattson	Mattson & Sons Well Drilling 9558 Straits Hwy Wolverine, MI 49799	
Mark Sawade	Sawade Drilling Company, Inc. 4066 E. River Rd. Mt. Pleasant, MI 48858	
Michael Wise	Tri-County Drillers, Inc. 5154 E. M-21 Corruna, MI 48817	
Robert Ward	S. Ward & Son, Inc. 6458 E. Washington Clarkston, MI 48346	
William Pearson	Pearson Drilling Co. 6100 W. Blue Road Lake City, MI 49651	
Miles Foune	Foune Well Drilling, Inc. 12642 CR 665 Bloomingdale, MI 49026	
Norm Buer	Buer Well Drilling, Inc. 239 E. Main St. Caledonia, MI 49316	

Steve McPherson	McPherson Well Drilling 10000 McPherson White Lake, MI 48382	
Gerald Neubecker	Raymer Company, Inc. 1357 Comstock St. Marne, MI 49435	
Jack Belt	WS Belt & Sons, Inc. 14430 Hough Rd Allenton, MI 48002	
Myron (Mike) Katz	Katz Well Drilling 1479 E. Michigan Ave. Battle Creek, MI 49015	Y

Information Transfer Program

Problem and Research Objective:
Information is now easily and readily available over the internet. However, the information may or may not be accurate, and in some cases, completely false. It is critical for Universities to be dependable sources that provide accurate, non-biased science-based information, whether that information is accessed via the web or is available in an alternate format. It must be current, reliable and readily transferable to a wide audience in formats that are easily understood. The Institute of Water Research has developed and expanded upon its information dissemination and training program addressing real-world water resources problems and issues and providing timely information to scientists, decision makers, farmers, riparians and other interested citizens throughout the state.

The objectives of the information dissemination and technology transfer program are to develop and present educational programs designed to increase the public's awareness and appreciation of the water quality and quantity problems in Michigan and to stress the economic trade-offs required to solve water related problems. These programs are offered in the form of conferences, training workshops, demonstrations, computer models and decision support systems, web-based programs, and printed material.

Methodology:
Methods used to meet the objectives are to: (1) sponsor state of the art conferences and workshops that deal with pressing water related issues; (2) prepare lecture/demonstrations, audio-visual materials; and power point presentations (3) develop training sessions and workshops to assess trends in water quality; (4) present web based programs that provide users with information and other data needed for decision making; (5) compile, interpret, and distribute water related information as well as directing users to appropriate sources of expertise and information; and (6) cooperate with the Michigan State University Extension Service to make water related information available through the county cooperative extension agents.

Principal Findings and Significance:
The dissemination portion has involved a number of technology transfer mechanisms such as seminars, workshops, and conferences; web based information systems, data and virtual courses; and pamphlets, exhibits and demonstrations. Each program is designed to make the latest information available to the appropriate user groups. Local, state, and federal agency personnel as well as students, staff, and others are given the opportunity to hear and interact with outstanding researchers and have access to a variety of written materials and multi-media presentations. Participants have been able to use the information gained from these programs in their decision-making processes concerning water resources.

Information Dissemination and Technology Transfer Training Programs

Basic Information

Title:	Information Dissemination and Technology Transfer Training Programs
Project Number:	2005MI58B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	8th
Research Category:	Water Quality
Focus Category:	Education, Groundwater, Surface Water
Descriptors:	Water Quality; Watershed Management; Macroinvertebrates; Volunteer Monitoring
Principal Investigators:	Lois G Wolfson

Publication

1. Taylor, William, Michael Schetcher, and Lois Wolfson (editors). In Review. Globalization: Effects on Fisheries Resources. Cambridge University Press, Cambridge, UK.
2. Bruhn, L. and L. Wolfson. 2006. Citizens Monitoring Bacteria: A Training Manual for Monitoring E. coli. Michigan State University, East Lansing, MI. 40 pp.
3. Moy, Jessica, William Hudson, Ruth Kline-Robach, Ashton Shortridge, Sarah AcMoody. 2006. Modeling Socioeconomic Data Sources to Estimate Non-Point Source Pollution. [poster]. Planning for Prosperity, Land Use Conference. East Lansing, MI.
4. Wolfson, Lois and Ruth Kline-Robach.. 2006. Water Quality Programs at Michigan State University [poster]. USDA CSREES National Water Quality Conference, San Antonio, TX
5. Iles, J., L. Wolfson, OBrien, E., B. Luikkonen, K. Stepenuck, L. Seigley, and L. Crighton. 2005. Bacteria Monitoring in the Upper Midwest: Developing Consistent Training and Monitoring Methods [poster]. USDA CSREES National Water Quality Conference, La Jolla, CA.
6. Ruth Kline-Robach. 2005 An Integrated Approach to Storm Water Management at Michigan State University. [poster]. USDA CSREES Water Quality Conference. LaJolla, CA.

Project Number: 2005MI58B
Start: 03/01/05 (actual)
End: 02/28/06 (actual)

Title: Information Dissemination and Technology Transfer Training Programs
Investigators: Lois G. Wolfson, Institute of Water Research, Michigan State University
Focus Categories: EDU, GW, SW, WQL
Congressional District: Eighth
Descriptors: Water Quality; Watershed Management; Macroinvertebrates; Volunteer Monitoring

Problem and Research Objective:
Information is now easily and readily available over the internet. However, the information may or may not be accurate, and in some cases, completely false. It is critical for Universities to be dependable sources that provide accurate, non-biased science-based information, whether that information is accessed via the web or is available in an alternate format. It must be current, reliable and readily transferable to a wide audience in formats that are easily understood. The Institute of Water Research has developed and expanded upon its information dissemination and training program addressing real-world water resources problems and issues and providing timely information to scientists, decision makers, farmers, riparian's and other interested citizens throughout the state.

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Methods used to meet the objectives are to: (1) sponsor state of the art conferences and workshops that deal with pressing water related issues; (2) prepare lecture/demonstrations, audio-visual materials; and power point presentations (3) develop training sessions and workshops to assess trends in water quality; (4) present web based programs that provide users with information and other data needed for decision making; (5) compile, interpret, and distribute water related information as well as directing users to appropriate sources of expertise and information; and (6) cooperate with the Michigan State University Extension Service to make water related information available through the county cooperative extension agents.

Principal Findings and Significance:
The dissemination portion has involved a number of technology transfer mechanisms such as seminars, workshops, and conferences; web based information systems, data and virtual courses; and pamphlets, exhibits and demonstrations. Each program is designed to make the latest information available to the appropriate user groups. Local, state, and federal agency personnel as well as students, staff, and others are given the opportunity to hear and interact with

outstanding researchers and have access to a variety of written materials and multi-media presentations. Participants have been able to use the information gained from these programs in their decision-making processes concerning water resources.

Project Relevance

Michigan is fortunate to have an abundant and widespread supply of water due in large part to its geographical location within the Upper Great Lakes Region. Although relatively plentiful, the high demand on and use of the water resources in the state often result in both water quantity and water quality problems. As activities within the state continue to increase, the state's water resources continue to be at risk.

As impacts on water quality become more widespread, the need for action at the watershed level becomes more apparent. The movement of pollutants across a watershed is not constrained by political boundaries, and activities in one political jurisdiction may lead to water degradation in another. Further, water withdrawals from both surface water and groundwater may result in decreased stream flow and reduced lake levels and lead to both water quantity and quality problems. The difficulty in assessing impacts from erosion, nonpoint source pollution, water withdrawals or shoreline development lies not only in the magnitude of the data collection efforts, but in the proper analysis and interpretation of the data needed for assessing the problem.

In order to stay informed about water quality changes over time, and to determine if efforts being made to reduce pollutants are proving effective, an education, monitoring, and evaluation program is appropriate. An effective information dissemination and training program facilitates the transfer of information needed to protect the water resources in the state, and helps to inform scientists, legislators, and citizens of the most recent information available. For further effectiveness, agency personnel, riparian's, educators and others interested in protecting their water resources or in teaching others about it must understand the importance of collecting and/or analyzing information at the watershed level to ensure that reliable and appropriate information is being used to make sound decisions for water quality protection.

Project Objectives

The Institute of Water Research has a long history of providing effective information dissemination and training programs. These programs have involved close cooperation with other groups and organizations within the University and the state in order to enhance their effectiveness. Partnering with other groups has become a critical component for successful programming and delivery. Because educational levels and prior knowledge in the subject area are so varied, a number of transfer mechanisms are necessary. With the increasing use of web-based programs, the Institute has put much of its resources into providing access to data, papers, models, programs, and other types of information that can be successfully accessed and utilized on the web. Other traditional methods such as conferences, workshops, written publications, and self-contained computer programs are utilized for both lay audiences and professional groups throughout the state. Training sessions are also offered to provide hands-on experience for a number of diverse audiences.

The following objectives relate to information dissemination programs arising from water-related activities at the Institute of Water Research.

1. Utilize the dissemination potential of the web by developing educational modules; interactive models; and virtual reality courses.

2. Develop and present educational programs such as conferences, seminars, and training workshops designed to increase the public's awareness and appreciation of the water quality problems in the state and to stress the economic trade-offs required to solve any problem.

3. Prepare lecture/demonstrations for presentations to college classes, secondary and elementary schools, and private groups on such topics as watershed management, wastewater treatment, wetland and lake ecology, water conservation, and groundwater contamination.

4. Cooperate with the Michigan State University Extension to make water-related information available through the cooperative extension network.

Program Results
Since the Institute of Water Research Information Dissemination and Technology Transfer Program began in the early 1970s, it has been responsive to the informational needs of a wide variety of user groups. Many modes of information exchange have been used to further this program and provide the latest research information to user groups. The following programs were developed and delivered for fiscal year 2005-2006.

Conferences, Workshops and Symposia
The Great Lakes are continuously faced with a multitude of threats that can degrade both their water quality and recreational potential. The IWR co-sponsored the 15th annual Great Lakes conference, titled: *Invaders of the Great Lakes: Options for Prevention and Management.* As implied in the title, the conference focused on current research and activities of agencies, Universities and organizations working on aquatic nuisance species. Four out of state speakers presented their research on the Invasion History and Risks in the Great Lakes ecosystem, the Chicago Barrier, Round Goby and Hydrilla. Four speakers from Michigan addressed current scientific research relating to zebra mussel-blue-green algae interactions, food web disruptions, sea lamprey, and non-indigenous species and the aquaculture industry. A keynote presentation on a state resource management perspective on aquatic invasives in the Great Lakes was given by the Director of the Michigan Department of Natural Resources. The Office of the Great Lakes, Michigan Department of Environmental Quality and the Michigan Chapter of the North American Lake Management Society cosponsored the event which attracted nearly 200 participants.

The Institute helped sponsor the seminar/workshop series *Shaping Future Water Policy: The Role of Science*. The series, developed by the Homer Nowlin chair of Water Resources was designed to bring together nationally renowned water scientists and individuals (Water Resource Fellows) who were interested in and could play a role in the future of water in the State of Michigan. Invited scientists introduced the latest scientific knowledge and cutting-edge technologies to address water problems and participated with the Fellows on discussions about the future investment and type of information needed for making science-based policy decisions. IWR staff served as recorders for all sessions and provided input during the forum.

A symposium was held during the American Fisheries Society annual conference in 2005. Titled *Fishing for the Future: Managing Fisheries and Aquatic Ecosystems using a Business Paradigm,* the conference featured speakers from the University and several Michigan agencies. An IWR staff member was involved with the planning and implementation of the symposium.

Volunteer Monitoring, Lake and Stream Leader's Institute, and Conservation Stewards Program
Two training programs were held to train volunteers in the sampling and analysis of *E. coli* in streams. Funding from another source was obtained for this project, and IWR staff coordinated the technology transfer program with this project. Another program, the Lake and Stream Leader's Institute graduated its second class in 2005. Four sessions were held during the season and helped train local water/land resource leaders in leadership, management of lakes and stream, local government actions, riparian law and mediation. IWR staff personnel played a significant role in both the development and implementation of this program and worked in concert with the other coordinators. IWR staff members led a hands-on session on macroinvertebrate identification and one in general lake ecology. Other involvement included conference logistics, helping to develop a web page for the class and serving on the advisory committee. IWR staff also provided the Lake and Stream Ecosystem Management portion of the program for the Conservation Stewards program. This 12 week course, offered in two different counties, provided high quality, locally-based education opportunities to create an informed Michigan citizenry who could then provide volunteer conservation management activities within their community. All participants received power point presentations, reference materials, hands-on opportunities, and the chance to interact with a variety of experts and other volunteers. Approximately 65 participants took the course

Water Quantity and Water Use
The Institute recently brought in several consultants to assist with facilitation of a project on restoring Great Lakes Basin waters through conservation credits and integrated water balance analysis system. The consultants briefed the advisory team, composed of representatives from business and industry, state government, environmental organizations, agriculture, planning agencies, citizens, and policy makers on groundwater policy in the eastern US and helped the group with decisions concerning the development of an innovative system of water conservation credits which will help policy makers manage water resources to meet the demands of water uses, conservation, and the improvement of ecological sustainability. Additionally, the IWR briefed the Natural Resources and Environmental Policy Committees on groundwater science and spoke at several hearings. Results from these discussions and hearings helped the legislature to pass five new groundwater bills in Michigan.

Great Lakes Camp
The Institute helped MSU Extension and 4-H at its annual Great Lakes camp. This one entire week event, located next to Lake Huron, promotes science, leadership, and educational and career development for youth. IWR staff developed and ran the Watershed and Lake Ecology session. Approximately 60 students attended the camp.

Internet-Based Programs
IWR staff members have maintained their presence on the web through their decision support system development. Programs such as the Watershed Mapping program, both in Michigan (www.iwr.msu.edu/water) and throughout the US (www.iwr.msu.edu/dw) are continually being improved upon and expanded to make more data readily available as well as comprehensive. Efforts are underway to incorporate additional models into the system, and staff continue to work with Purdue University on a variety of sediment and hydrologic models. The staff also continues to add linkages to other programs that provide data resources. For example, the Terra Server has enabled the Institute to access digital orthoquad photographs in any area of the continental United States and use them in the digital watershed program.

Exhibits and Demonstrations
IWR staff members took part in various programs hosted by other University units or outside agencies. The IWR participated in the Michigan Science Olympiad by serving as the State Supervisor for Water Quality in the state finals. This annual event included 48 junior high and high schools who competed in a variety of science related events. Winners of the event continued to the national finals.

In late July, MSU's Ag Expo, an agricultural oriented exposition was held. Approximately 35,000 people attended the event. Each year the Institute features an educational exhibit. Due to the large demand for its web based services, the IWR again featured its web-based programs, “Understanding Your Watershed”. Participants were able to overlay several layers of data, such as wetlands, rivers, streams, or watershed area onto digital rectified aerial photograph of their property. The IWR worked closely with the MSU Land Policy Program. Approximately 1000 people visited the multi-departmental tent over the three day event.

The IWR also continued its participation in the Children’s Water Festival, an event that brings together nearly 2000 elementary school children from across the tri-county area to be introduced to a variety of natural resources and science-related topics. The IWR led two topic areas, one featured aquatic macroinvertebrates and their role as water quality indicators, while the other focused on aquifer vulnerability and used ice cream, dyes, and candy to depict aquifers and contaminants. Six classes for each topic were held with 25 to 40 students per class.

Lectures and Seminars
The Institute staff gave many presentations in FY05-06 on issues such as ecosystem health, E. coli sampling, wellhead protection, indicator species for water quality testing, watershed management plans, and exotic species introduction. Audience participants included legislators, community personnel, watershed managers, students, and interested citizens. Staff gave class lectures in the Departments of Fisheries and Wildlife, Community, Agriculture, Recreation and Resources, and Journalism, and Zoology. Audience or class participation varied.

Personnel and Facilities
The Institute of Water Research maintains such facilities and equipment as the latest software packages for desktop publishing, GIS, video editing and photographic equipment to support its Information Dissemination Program. It also has microcomputers, four Sun Sparc-20 work station, a graphic plotter, scanner, color printer, and digital camera to enhance its educational

programs. For field demonstrations and research related opportunities the Institute also has a Data Sonde mini-probe for measuring chemical parameters in lakes. The Institute's technology transfer program is under the direction of Principal Investigator Dr. Lois Wolfson, with several Institute personnel contributing to the project, including Dr. Jon Bartholic, Ruth Kline-Robach, Laura Bruhn, and Jeremiah Asher.

Publicizing, Facilitating the Access, and the Interpretation of the Michigan Groundwater Inventory and Mapping Project with Outreach Education

Basic Information

Title:	Publicizing, Facilitating the Access, and the Interpretation of the Michigan Groundwater Inventory and Mapping Project with Outreach Education
Project Number:	2005MI59B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	8th
Research Category:	Ground-water Flow and Transport
Focus Category:	Education, Water Quantity, Water Use
Descriptors:	Hydrology, Water Use Conflicts, GIS, Groundwater
Principal Investigators:	William J. Northcott, Pamela KB Hunt, Steve Miller

Publication

Synopsis

Project Number: 2005MI59B
FY 2005 Federal Funds: $15,000 **FY 2005 Non-Federal Funds**: $30,777
Start Date: 03/01/05 **End Date**: 02/28/06
Title: Publicizing, Facilitating the Access, and the Interpretation of the Michigan Groundwater Inventory and Mapping Project with Outreach Education
Project type: Research
Principal Investigator: William J. Northcott, Asst. Professor, Dept. Ag Engineering
Focus Categories: Water Quantity, Water Use, Education
Congressional District: Eighth
Key Words: Hydrology, Water Use Conflicts, GIS, Groundwater

Publicizing, Facilitating the Access, and the Interpretation of the
Michigan Groundwater Inventory and Mapping Project with Outreach Education

Problem and Research Objectives

The state of Michigan recently enacted Public Acts 148 and 177, which focuses on water use. Public Act 148 outlines a strategy to assess the water resources of the State utilizing existing data. The second public act, 177, establishes the mechanism to resolve disputes among groundwater users and allows the government to intercede if large water withdrawals are threatening the water resource. Educational outreach is not a component that has been included in any of the legislative initiatives. The general public needs to be informed of the published map series as well as the end users. The value-data base compiled into a map series of hydrogeologic parameters will need to be comprehensible to the public and their respective policy makers at all levels of government to aid in the understanding of these map presentations as well implementing the strategies stated in Public Act 177. Also, an explanation of what the scope of use for the map series needs to be disseminated with an outreach educational goal of interpretation and the limits applied to each map. This year the legislature has proposed legislation to require the permitting and regulation of large water withdrawals entitled the Water Legacy Act. The proposed measures would fulfill part of the Great Lakes Charter, an agreement between the eight states and two Canadian provinces bordering the Great Lakes, by regulating bulk withdrawals from the Great Lakes, inland lakes, rivers, and aquifers. Michigan is the only partner in the charter that has not committed to legislation of regulating and limiting the large water withdrawals from the surface or ground water resources or preventing the diversion of the Great Lakes. The media coverage of the Great Lakes and ultimately our water resources are being debated throughout the state by various mediums including the opinion pages, newspaper articles, meetings and briefs sponsored by special interest groups and policy makers seeking scientific conclusions and constituent's views. Michigan citizens and their legislators are a receptive audience to our proposed efforts to publicize, facilitate the access and to interpret the map series of the groundwater inventory.

Methodology, Principal Findings, Significance
The highly publicized court case in West-Central Michigan concerning a citizen's group alleging that large water withdrawals by a bottling plant is negatively impacting the surrounding water resources. Also, mining operations in the Southeast Michigan have resulted in lowering the

water levels in the area affecting neighboring wells. In East-Central Michigan, irrigation is being charged with lowering the water levels in the nearby domestic wells and influencing the upward intrusion of saltwater from a bedrock aquifer. Thus, the public's perception of an unlimited water supply and sustainable water resources is being altered by these published events of conflicting water uses. Recent environmental legislation enacted by Michigan addresses the need for an inventory of hydrogeologic data, and adopting strategies for water use conflicts, Public Act 148 and 177 respectively. Currently, proposed legislation, entitled the Water Legacy Act, has been submitted in the Michigan House and Senate subcommittees. This proposed legislation would fulfill part of the Great Lakes Charter, an agreement between the eight states and two Canadian provinces bordering the Great Lakes, by regulating bulk withdrawals from the Great Lakes, inland lakes, rivers, and aquifers. Michigan is the only partner in the charter that has not committed to legislation of regulating and limiting the large water withdrawals from the surface or ground water resources or preventing the diversion of the Great Lakes. The problem with the current and proposed legislative initiatives is the fundamental component of outreach education is overlooked. The groundwater inventory and map series will be available on a web site as directed by the statutes; but, the majority of the public sector will not be aware of the available data inventory and lack the background knowledge to understand or interpret the presented information.

Statement of results or benefits

The U.S. Geological Survey (USGS) and Michigan State University (MSU) will aid the Michigan Department of Environmental Quality (MIDEQ) in completing the requirements of section 32802 of Public Act 148 by the summer of 2005. The following requisite components to complete the inventory and a map series are:

- Location and water yielding capabilities of aquifers in the state
- Aquifer recharge rates in the state
- Static water levels of groundwater in the state
- Base flow of rivers and streams in the state
- Conflict areas in the state
- Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources that are identified on the natural features inventory
- Location and pumping capacity of specific facilities
- Aggregate agricultural water use and consumptive use, by township
- Groundwater inventory and map available to the general public

The inventory and mapping project extracts, analyzes, and maps data from well record records stored in the Wellogic data base. Base flow and aquifer recharge is derived from USGS studies. Water use data and information on water use conflicts are provided by MIDEQ. The groundwater inventory mapping project will provide the tools for environmental planning. If outreach materials are developed to present a scientific framework of Michigan's water resources, the majority of the consumers, water resource managers, and policy makers will be more receptive to accept voluntary and legislative to protect and manage their water resources.

Nature, Scope, and Objectives of The Project, Including a Timeline of Activities

The delivery of outreach education is evolving due to computer technology available to the mainstream public. Even though data is available on web sites, the applicable explanations are often not rationalized or clarified. When metadata is accounted for, most users are not able to comprehend the descriptive information into laymen's terms. Thus, the main objective of this outreach proposal is to summarize the groundwater inventory and map for the non-scientific sector as an aid in understanding the fundamental concepts of Michigan's water resources by a variety of methods. Networking with agencies such as the MSU extension staff and Michigan Department of Agriculture, outreach educational deficiencies and needs have been identified and will continue to be noted to the IWR.

The delivery of outreach education was accomplished by the following initiatives:

- A project overview and appraisal meeting was held March 1, 2005 at the Kellogg Center on the campus of MSU. Representatives from an array of stakeholder groups were invited including water supply consultants, well drilling contractors, academic hydrogeologists, local environmental health and the DEQ technical advisory group. Preliminary copies of the Glacial Aquifer and Bedrock Aquifers Yield maps were displayed at the March 15, 2005 annual meeting of the Michigan Groundwater Association. About fifty people viewed the maps and twelve made written comments concerning groundwater conditions in their various service areas.
- The Department of Biosystems and Agricultural Engineering Newsletter featured an article the Michigan Groundwater Inventory and Mapping Project. (article attached)
- Three meetings with Extension Coordinator, Dean Solomon, to discuss deliverables for Extension personnel and publications. (brochure attached)
- The 26th annual Ag Expo, Michigan's largest and most inclusive farm equipment and trade show, took place July 19-21 on the campus of Michigan State University. This event draws nearly 15,000 farmers and members of farm-related groups and their families annually. Our booth featured IWR's products including online demonstrations for the GW Mapping Project at <http://gwmap.rsgis.msu.edu/> and Understanding your Watershed at <http://www.iwr.msu.edu/>. (posters attached)
- In our educational tent at the Ag Expo, a GW Mapping Project "feature presentation" was delivered on July 20, 2005 to the attendees.
- Presented at the Water Quality Area Of Expertise Summer Retreat, Monday and Tuesday, August 22 and 23, 2005, (agenda attached)
- Attended 2005 Water Resources Conference, Use of Long-Term Research for Enhancing Water Quality in the Great Lakes Region, Regional Water Quality Meeting September 8 and 9, 2005 University Place Conference Center at IUPUI Indianapolis, Indiana. Attendees included those with interest in water quality research, extension, and urban water resource activities as well as those interested in using water quality data in a decision making process. Sponsors included USDA-CSREES though the Great Lakes Regional Water Quality Leadership Team, Indiana Water Resources Research Center (IWRRC), and the Center for Earth and Environmental Science (CEES) at IUPUI.
- MSU's Role in Water Use Policy Meeting to discuss how our presence (MSU) can be made known to the legislature and to determine how we can bring science based information to decision makers, November 22, 2005
- Groundwater Mapping Training session, February 14, 2006 (agenda and brochure attached)

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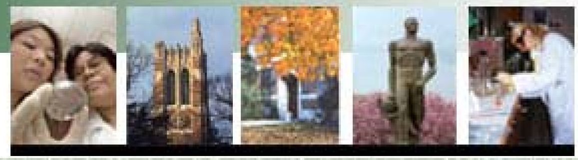
Department of Biosystems & Agricultural Engineering

Newsletter



Department Newsletter

January - February, 2006

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THE MICHIGAN GROUNDWATER INVENTORY AND MAPPING PROJECT

By: Steve Miller, BAE
Dave Lusch, RSGIS
Pam Hunt, IWR

Printable pdf

In response to growing concerns about groundwater use conflicts, in 2003 Michigan Public Act 148 of 2003 was enacted. The act required the Department of Environmental Quality (DEQ) to create a "groundwater inventory and map" that includes eight specific map components, a general requirement for a groundwater inventory, and a directive to make the map and inventory available to the public. DEQ established a collaborative research team involving groundwater and mapping experts from the U.S. Geological Survey (USGS) and Michigan State University (MSU). The project team designed an interactive web site to make the mandated products available to the public to aid in understanding and evaluating the groundwater resources in Michigan .

The interactive web site's home page (http://gwmap.rsgis.msu.edu/) links to the following components for the Groundwater Mapping Project.

- **Interactive Map Viewer** - access the spatial map layers as well as query databases. The mandated map components are:
  - Location and water yielding capabilities of aquifers in the state - glacial yield, glacial transmissivity, glacial draw down, bedrock yield, bedrock transmissivity, and bedrock draw down
  - Aquifer recharge rates in the state
  - Base flow of rivers and streams in the state
  - Water levels of groundwater in the state
  - Surface waters, including designated trout

Groundwater Inventory and Mapping Project

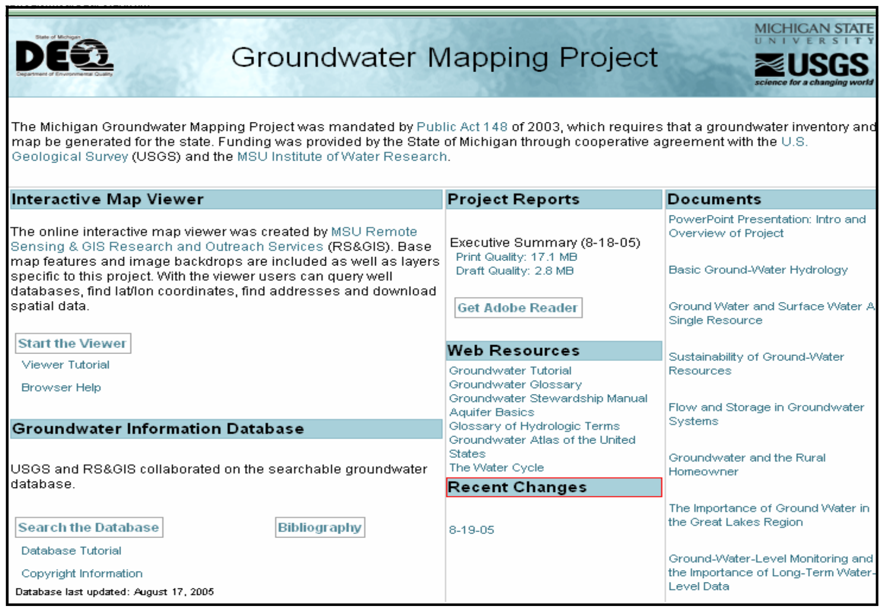
What is the Groundwater Inventory and Mapping Project?

Michigan Public Act 148 of 2003 required the Department of Environmental Quality (DEQ) to create a "groundwater inventory and map" that includes eight specific map components, a general requirement for a groundwater inventory, and a directive to make the map and inventory available to the public. DEQ created a cooperative research team involving groundwater and mapping experts from the U.S. Geological Survey (USGS) and Michigan State University (MSU). This project team designed an interactive web site to make the mandated products available to the public. The site can be used to answer questions of groundwater availability in Michigan. Some examples are featured in this fact sheet.

The web site's home page (on the right) links to the completed products for the Groundwater Mapping Project.

http://gwmap.rsgis.msu.edu

- Interactive Map Viewer
  (specific map components & wells summary)
- Groundwater Information Database
  (query publications & bibliography)
- Project Reports
- Web Resources
- Recent Changes
- Documents



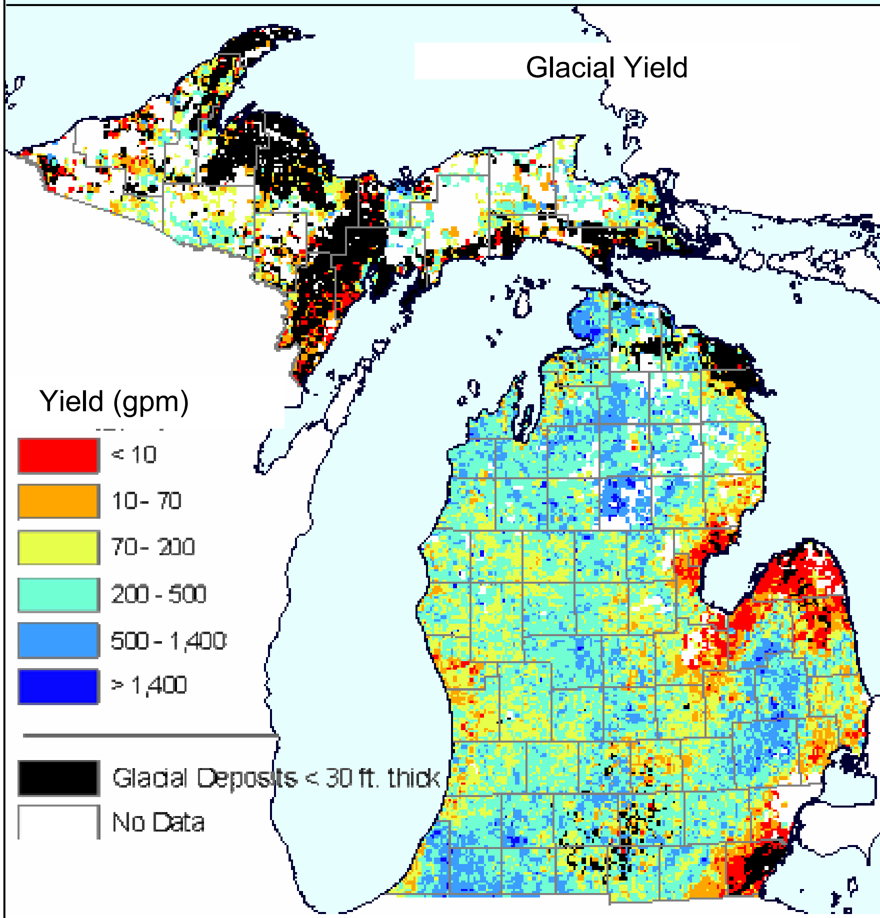
What are the specific map components?

The Interactive Map Viewer features the requisite map components:

- Location and water yielding capabilities of aquifers in the state
  glacial yield, glacial transmissivity, glacial drawdown, bedrock yield, bedrock transmissivity, and bedrock drawdown
- Aquifer recharge rates in the state
- Static water levels of groundwater in the state
- Base flow of rivers and streams in the state
- Conflict areas in the state
- Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources that are identified on the natural features inventory
- Location and pumping capacity of specific facilities
- Aggregate agricultural water use and consumptive use, by township
- Supplemental maps: Glacial Landsystems, Wells Summary database, Wells-Complete database, Wells-Hydrologic Properties database

Each of these maps contain layer information and metadata

How abundant is groundwater in the glacial deposits?

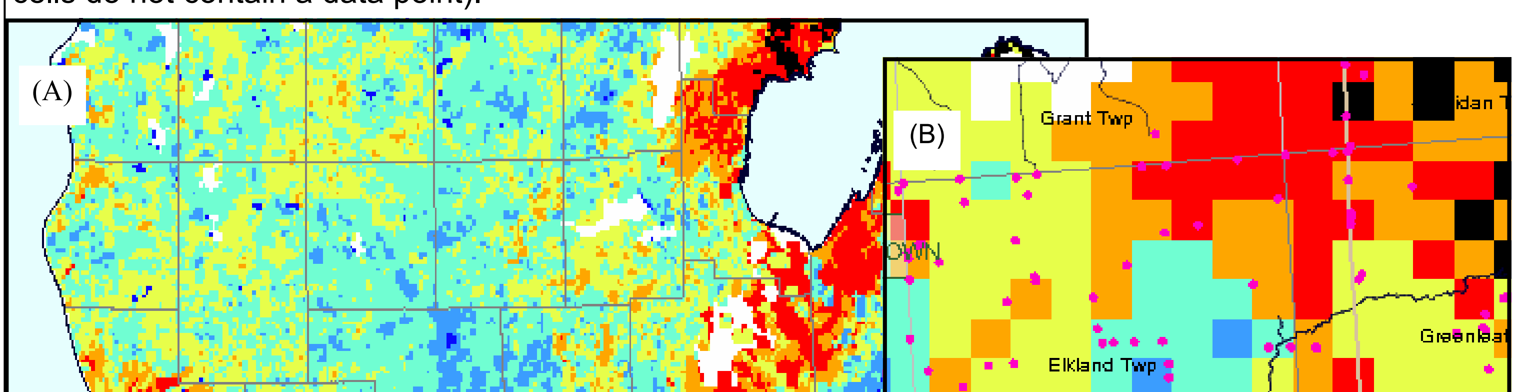


The industry-standard minimum well yield for a small residential home is 10-15 gpm. The 70 gpm yield level is the current definition of a high capacity well.

Several regions of minimal yield, <10 gallons per minute (gpm), are obvious on the Glacial Yield map on the left, most notably in the areas northwest, south, and southeast of Saginaw Bay, the tip of the "thumb", and southeastern most Lower Michigan. Many areas in Delta and Menominee counties in the Upper Peninsula also exhibit poor yields. Note that in these areas, some homeowners have wells in glacial deposits that yield sufficient water. Local-scale heterogeneity (lithologic variations within 10-1000 meters) is very difficult to quantify and display on a statewide map. As such, site-specific investigation is always prudent when planning high-capacity groundwater withdrawals.

High capacity wells are routinely possible throughout much of Lower Michigan (excluding the areas shown in red and orange). Zones of very high yield potential are located in southwestern and south-central Lower Michigan, in the core of the "thumb" (Oakland, Lapeer and southeastern Tuscola counties), in the Houghton-Higgins lakes district of northern Lower Michigan and across the "tip of the mitt."

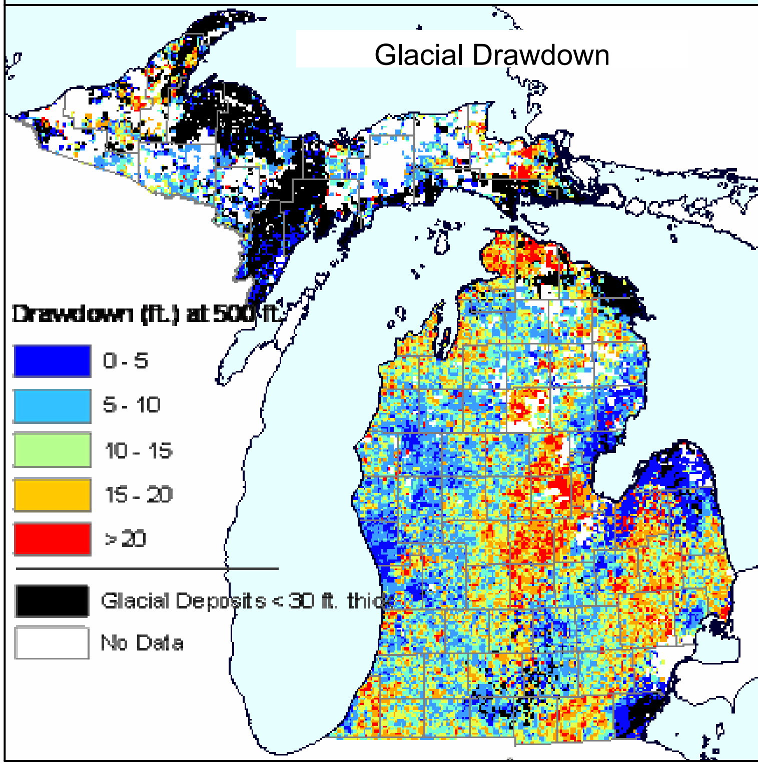
The "Full Extent" view as shown above for the Glacial Yield Map is primarily useful to observe the gross, statewide patterns of the theme and navigating to a closer view. In most cases, the inherent detail of the theme cannot be observed at this small presentation scale. Zooming in on about a third of the state (A) makes the individual 1 km^2 grid cells of this theme just visible and heterogeneous areas (many different colors side by side) become more obvious. Zooming in until the vertical dimension of the viewer window encompasses a few townships (B) makes the individual grid cells very obvious. At this and larger presentation scales, the water well point file ("Wells Summary DB") can be displayed and gives the map reader a better appreciation of the "control" that exists for the interpolation of the data (note that many cells do not contain a data point).



WELLS SUMMARY

WELLID	IMPORT_ID	COUNTY	TOWNSHIP	TOWN_RANGE	SECTION	OWNER_NAME	WELL_ADDR	WELL_DEPTH	WELL_TYPE
33000006374 Lith Info	33040224002	Ingham	Lansing	04N 02W	24	MSU POULTRY RESEARCH	3606 E MT. HOPE RD.	352	*U

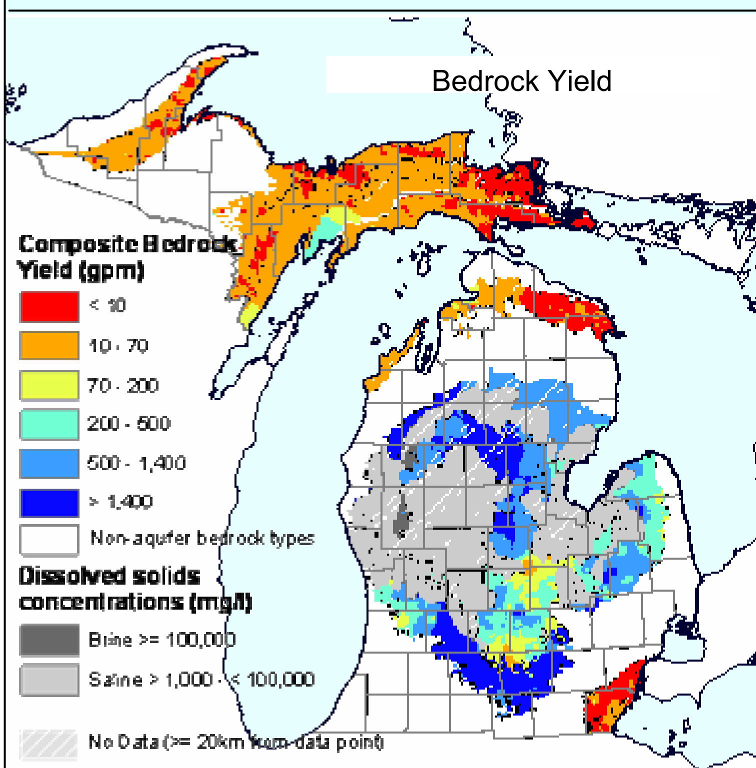
What is the probability that a high capacity well will adversely impact a small capacity well in the glacial deposits?



The estimated drawdown map for pumping from glacial deposits follows the general patterns noted for the yield map (shown on left hand page) with one interesting exception. Areas of low estimated drawdown (less than 5 ft) occur both where the estimated yield is moderate (70-200 gpm) and where it is low (<10 gpm). In the low-yield areas, the small estimated drawdown results from the inability of the water-bearing materials to provide enough groundwater to impact a well 500 feet away.

In areas of moderate yield, the available drawdown and transmissivity of the glacial deposits are such that the estimated yield can be obtained without significantly lowering the groundwater level 500 feet away. In these areas, a high capacity well capable of pumping at a rate larger than the estimated yield might be possible (for example, by drilling a well much deeper than the typical wells in the area) and such a well could impact groundwater levels 500 feet away.

How abundant is groundwater in the bedrock deposits?



The bedrock aquifer map depicts those areas of the state where groundwater is readily available from the bedrock. The highest estimated yields from bedrock aquifers occur in the central and southern portions of the Lower Peninsula especially in Jackson, Calhoun and Barry counties where high yields are associated with a productive sandstone unit (Marshall Formation).

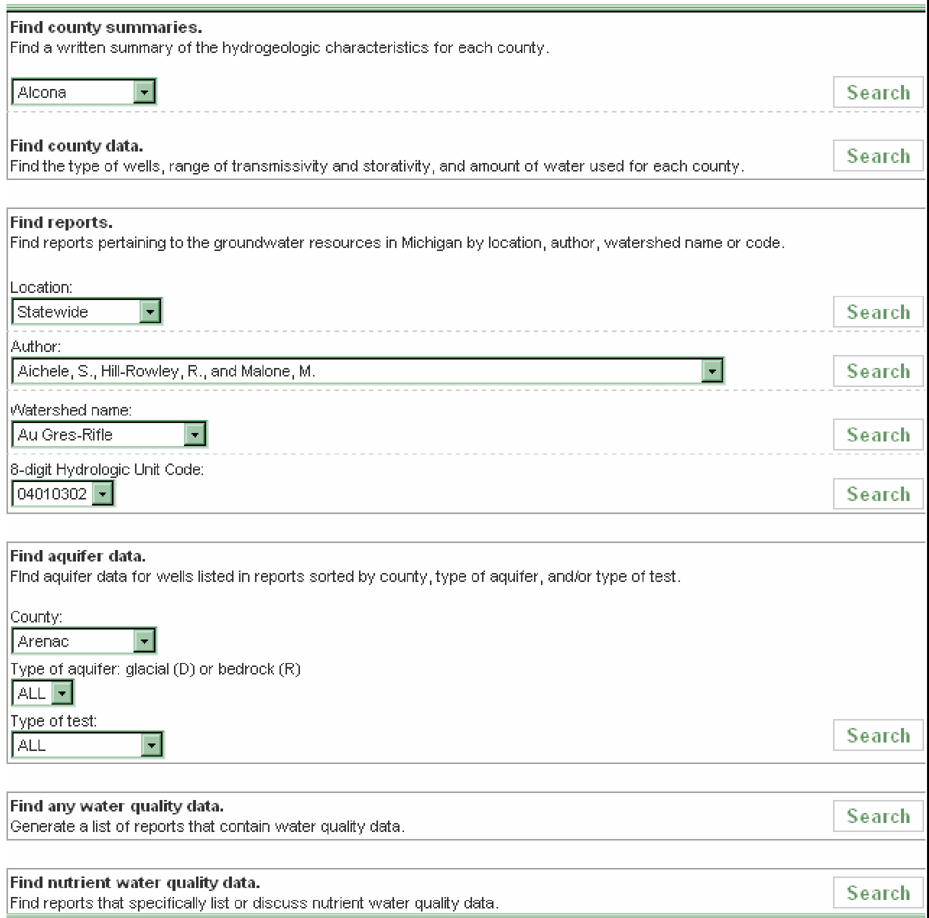
Lower yields are typical from bedrock aquifers in the Upper Peninsula, the northern swath of the Lower Peninsula and the southeast corner of the state. These aquifers are generally comprised of sandstone and carbonate units in the Upper Peninsula and predominately carbonate strata in the Lower Peninsula.

In the Lower Peninsula, the white areas are generally characterized by shale bedrock units that normally do not serve as aquifers, such as the Coldwater Shale that underlies much of southwestern and southeastern Lower Michigan and an arcuate swath from Mason to Alcona counties in the northern Lower Peninsula. Much of the western Upper Peninsula is dominated by hard-rock units that only produce groundwater along localized fracture traces. Nevertheless, there are residential wells in these areas of the State that derive water from fractures in the upper part of these “non-aquifer” units.

How can I search the available information that describes groundwater characteristics in Michigan?

The project team searched the available literature for relevant theses, journal articles, abstracts, conference presentations/papers, and government documents describing groundwater characteristics in Michigan. The bibliography contains 464 citations with over 220 digitally scanned documents.

Several search options are available on the Groundwater Information Database. Click on the link, **Search the Database**, the picture on your right shows all of the available search options.

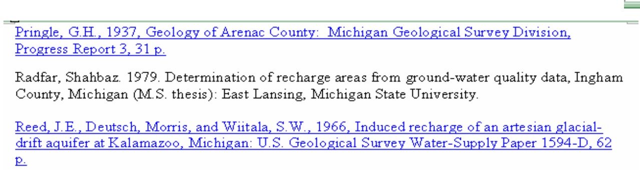


A hydrogeological summary is available for each county. The county summary describes the site location within the State and the watersheds located within the county. The glacial and bedrock deposits are described for the county. A search for county data will access type of wells, range of transmissivity and storativity, and amount of water used for each county.

Reports cited in the summaries can be accessed by location, author, watershed name or by a hydrologic unit code.

Aquifer data for wells listed in reports can be searched by county, type of aquifer, and type of test.

A list of reports that contain water quality data can be generated.


Pringle, G.H., 1937, Geology of Arenac County: Michigan Geological Survey Division, Progress Report 3, 31 p.

Radfar, Shahbaz. 1979. Determination of recharge areas from ground-water quality data, Ingham County, Michigan (M.S. thesis): East Lansing, Michigan State University.

Reed, J.E., Deutsch, Morris, and Wiitala, S.W., 1966, Induced recharge of an artesian glacial-drift aquifer at Kalamazoo, Michigan: U.S. Geological Survey Water-Supply Paper 1594-D, 62 p.

The full bibliography is also available on the Groundwater Information Database, excerpt shown at left.

The inventory and map products are available to end-users in three ways.

(1.) Web-based mapping site hosted by MSU (gwmap.rsgis.msu.edu). The digital data are also available for download from this site.

(2.) Digital data provided on compact disc for use with the Map Image Viewer software, an easy-to-use GIS software package for viewing and analyzing spatial data. MSU provides this mechanism. There is a charge for this service for users other than local health departments and the DEQ.

(3.) The digital data will also be available for download through the State of Michigan, Center for Geographic Information (www.michigan.gov/cgi).

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RS&GIS Biosystems & Agricultural Engineering Seeking Sustainable Solutions

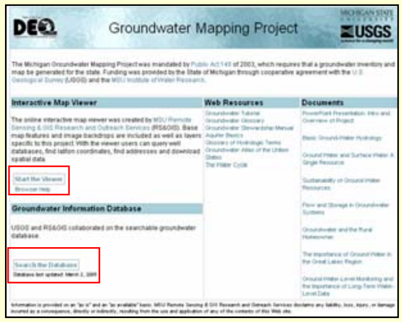
MICHIGAN STATE UNIVERSITY

State of Michigan DEQ Department of Environmental Quality

Groundwater Mapping Project

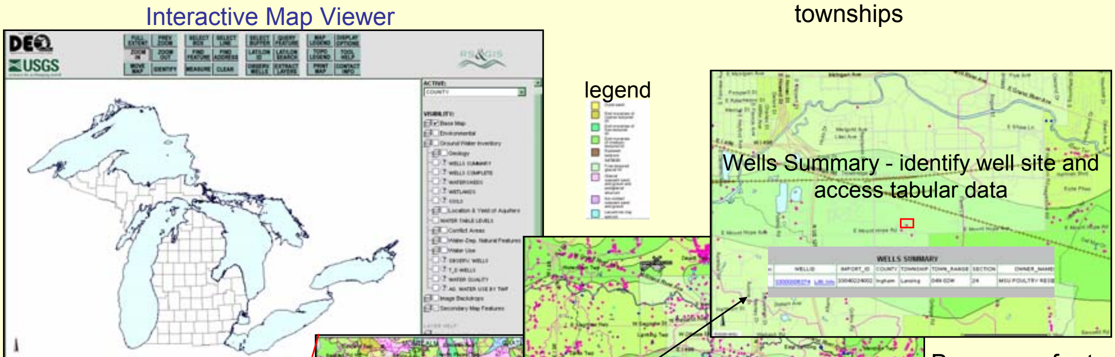
Groundwater inventory and maps available at: http://gwmap.rsgis.msu.edu/

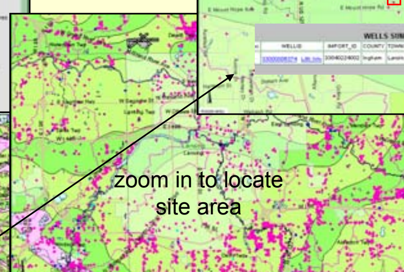
- Aquifer recharge rates
- Base flow of rivers & streams
- Location and water yielding capabilities of aquifers
- Static water levels of groundwater
- Conflict areas in the state

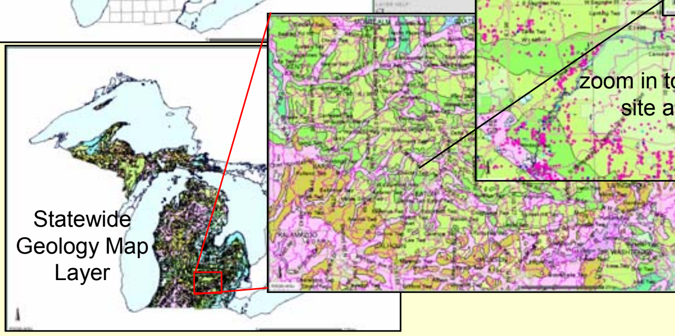


- Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources identified by natural features inventory
- Location and pumping capacity of specific facilities
- Aggregate agricultural water use & consumptive use, by townships

Interactive Map Viewer

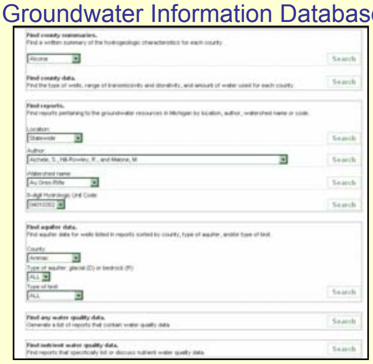






Base map features and image backdrops are included to use with the specific layers of the Groundwater Mapping Project. With the viewer, users can query well databases, find latitude/longitude coordinates, find addresses, & download spatial data.

Groundwater Information Database



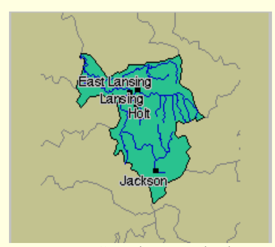
Click on the link, **Search the Database**. Several search options are available in this groundwater database. A county summary is available for each county as well as county data describing hydrogeological parameters. Publications cited in the summaries can be accessed and downloaded. Publications that contain aquifer data and water quality data can be seached as well.

A Sense of Place in Michigan's Watersheds

What is a Watershed? A watershed is the area of land that drains into a body of water such as a river, lake, stream or bay. It is separated from other systems by high points in the area such as hills or slopes. It includes not only the waterway itself but also the entire land area that drains to it. For example, the watershed of a lake would include not only the streams entering the lake but also the land area that drains into those streams and eventually the lake. Drainage basins generally refer to large watersheds that encompass many smaller watersheds. Each of these areas is considered to be a watershed at a certain scale and may be referred to as catchments, sub basins, sub watershed, or watersheds. Understanding how you impact a watershed is the first step toward protecting water quality. By being informed you can learn the simple things you can do as a homeowner or business owner to help improve water quality.

This diagram shows the larger watersheds or drainage basins in Michigan's lower peninsula. The Lansing, East Lansing, and Jackson areas are located within the Upper Grand Watershed, which eventually flows into the Lower Grand Watershed and then into Lake Michigan. Michigan is unique in that it is almost entirely contained within the Great Lakes Basin. Because of this there are many activities and projects at the IWR and all around Michigan which focus on improving the water quality in the Great Lakes Basin and its watersheds.

The Upper Grand watershed is a 572,376-acre watershed in parts of Hillsdale, Jackson, Eaton, Washtenaw, and Ingham Counties. Land uses within this watershed are about 6% agriculture, 20% urban, and 20% forestry. The Upper Grand River was once heavily polluted. The water quality has since been improved by decreasing point source and non point source pollutants. This has enhanced the fish and aquatic invertebrate community composition. Several portions of the Upper Grand River still fail to meet water quality standards. However, with proper surface and groundwater protection, land use, and watershed management planning, we can improve the water quality in the Upper Grand as well as other watersheds in Michigan.

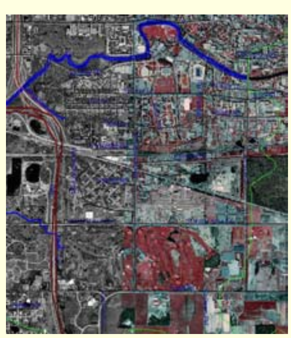


Upper Grand Watershed

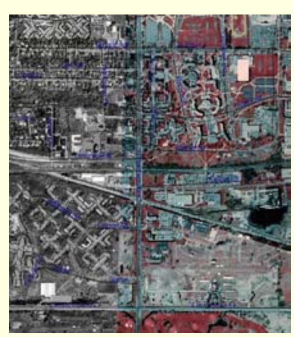
The Red Cedar River is the main flow of surface water in the Red Cedar Watershed in which MSU's campus is located. The Red Cedar River arises in Cedar Lake in the south-central Lower peninsula of Michigan and flows about 45 miles to its confluence with the Grand River in the city of Lansing. It has 12 tributaries and drains a total area of about 472 square miles. The river provides mid-Michigan residents with numerous recreational opportunities which include angling, canoeing, kayaking, photography and bird watching. The river also serves as a source of water for the irrigation of crops throughout the watershed.

These pictures show several scales of the Red Cedar Watershed in which we are currently located. You can obtain pictures and display various features of your watershed by visiting the IWR website, **http://www.iwr.msu.edu/**, and clicking on "Tools and Data" then "Watershed Mapping".

1 : 57,700



1 : 28,850



1 : 14,425

1 : 7,212

INSTITUTE OF WATER RESEARCH

MICHIGAN STATE UNIVERSITY

Agenda

Water Quality AOE Summer Retreat
Monday and Tuesday, August 22 and 23, 2005
Kettunen Center
14901 4H Drive
Tustin, MI 49688

Monday
9:30 AM – AOE Business meeting

Noon – Lunch in dining room

1:00 – 5:00 PM – Watershed and limnogical investigation using Center Lake, Osceola County
Howard Wandell, Lois Wolfson and Jane Herbert

6:00 PM Dinner in courtyard – evening free for boating, swimming, hiking, relaxing

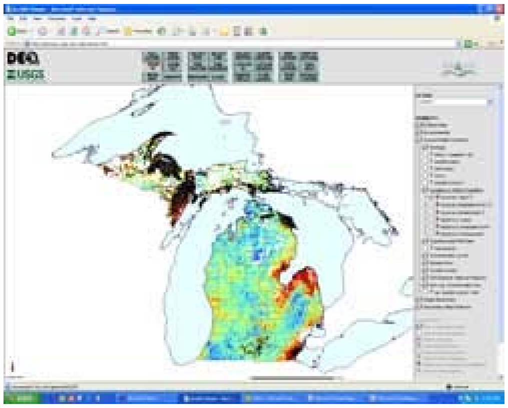
Tuesday
7:30 AM Breakfast in dining room – check out of rooms

8:30 AM New MSU Groundwater mapping tool (PA 148) – overview and in-service training
Dave Lusch, Steve Miller, and Pam Hunt

11:30 – Lunch in dining room

12:30 – 3:30 PM Meet with Jerry Lindquist, Osceola County ANR Educator, and then leave for MAEAP/CAFO visit

3:30 PM Return to Center or leave for home directly from farm



Groundwater mapping project web site training
Tuesday, February 14, 2006
Geography Building
Michigan State University

The Michigan Groundwater Mapping Project was mandated by Public Act 148 of 2003, which required that a groundwater inventory and map be generated for the state. The resulting web site, developed by the MSU Remote Sensing & Geographic Information Science Research and Outreach Services (RS&GIS) in cooperation with the MSU Institute of Water Research (IWR), USGS and MDEQ, includes a wealth of useful information and tools for agriculture and natural resources professionals, local leaders and landowners.

The Groundwater Mapping Project web site can help you:

- find specific information about wells in your community
- learn about groundwater use and availability in your community
- access past groundwater reports and studies
- access aerial photographs and map features
- predict drawdown from wells
- locate groundwater-dependent resources such as trout lakes and streams, and certain wetland types

Join us for this special in-service training to help MSU Extension and Michigan Groundwater Stewardship Program staff members learn about the features of this systems and how to use the tools in their communities.

Resource people will be Dave Lusch (RS&GIS and IWR), Steve Miller (MSU Biosystems and Agricultural Engineering and IWR) and Pam Hunt (IWR).

Agenda

9:30 am - noon	Introduction to the Groundwater Mapping Project and web site • Project background • Web site overview • Features and data resources • Example applications and limitations
noon - 1:15 pm	Lunch on your own
1:15 - 4:00 pm	A hands-on session at computers for those who intend to extensively use the tool in their community.
4:00 p.m.	Adjourn

You may attend just the morning overview session or the whole day.

How to register

There is no fee for this program, but pre-registration on this web site is required. **Registration deadline is Tuesday, February 7**. Registration is limited, so sign up early!

Registration form

Directions and parking

Directions to the Geography Building. Parking passes will be mailed to you if you register before February 3. Otherwise, permits will be available at the program registration desk.

For additional information, contact Dean Solomon, phone 269-671-2412 x221.

The Michigan Groundwater Inventory and Mapping Project

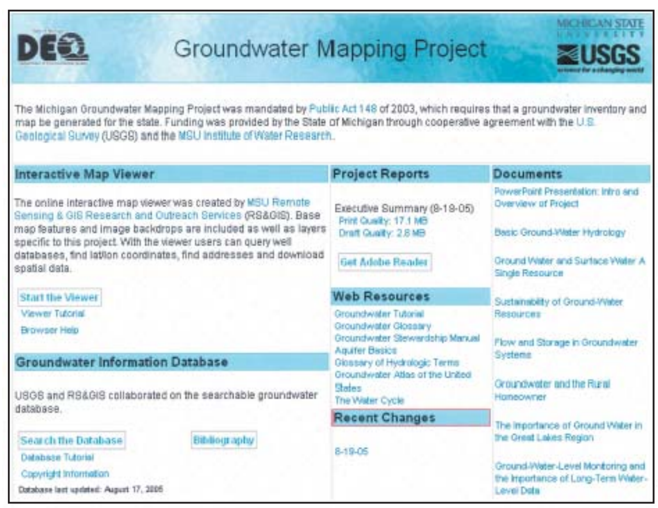
What is the Michigan Groundwater Inventory and Mapping Project?

The Michigan Groundwater Inventory and Mapping Project is a project to aid in understanding and evaluating the groundwater resources in Michigan and fulfills the mandates of Michigan Public Act 148 of 2003. The act required the Department of Environmental Quality (DEQ) to create a "groundwater inventory and map" that includes eight specific map components, a general requirement for a groundwater inventory and a directive to make the map and inventory available to the public. DEQ established a collaborative research team involving groundwater and mapping experts from the U. S. Geological Survey (USGS) and Michigan State University (MSU). The project team designed an interactive web site to make the mandated products available to the public.

The interactive website's home page (gwmap.rsgis.msu.edu) links to the following components for the Groundwater Mapping Project.

- **Interactive Map Viewer—**access the spatial map layers as well as query databases. The mandated map components are:
  - o Location and water yielding capabilities of aquifers in the state—glacial yield, glacial transmissivity, glacial drawdown, bedrock yield, bedrock transmissivity and bedrock drawdown.
  - o Aquifer recharge rates in the state.
  - o Base flow of rivers and streams in the state.
  - o Water levels of groundwater in the state.
  - o Surface waters, including designated trout lakes and streams, and groundwater dependent natural resources that are identified on the natural features inventory.
  - o Location and pumping capacity of specific facilities.
  - o Aggregate agricultural water use and consumptive use, by township.
  - o Conflict areas in the state.
  - o Supplemental maps: Glacial Landsystems, Wells Summary database, Wells-Complete database, Wells-Hydrologic Properties database.

  Additional map layers, including political boundaries, roads, aerial photos, topography, satellite imagery, land use, environmental sites and many more are available.
- **Groundwater Information Database**—access more than 220 articles digitally scanned and a bibliography with more than 480 groundwater relevant citations.
- **Project reports**—the Executive Summary contains a synopsis of the statewide conditions for each of the map components and inventory.
- **Web resources**—links to primers on groundwater and water resources.
- **Documents**—online documents concerning water resources.
- **Online tutorials**—for the Interactive Map Viewer and Groundwater Information Database.



Who can use this site and why?

Anyone with internet access can make use of this interactive website. The Michigan Groundwater Mapping Project website is targeted for a wide audience, for example, planners, watershed groups, policy makers, scientists, educators and citizens. This site can be used to investigate and evaluate areas of interest regarding the groundwater resources of Michigan.

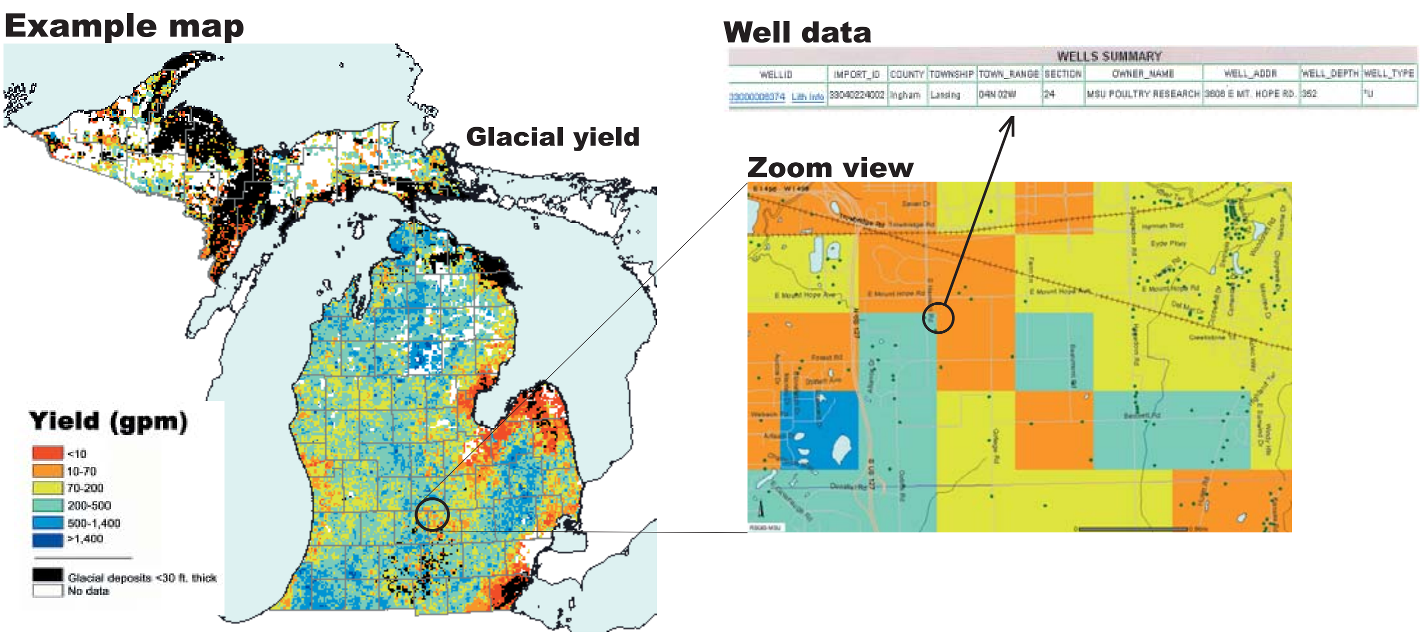
What kind of questions can be answered by the Michigan Groundwater Inventory and Mapping Project website?

- How abundant is groundwater in the glacial and bedrock deposits?
- What is the probability that a high capacity well will adversely impact a small capacity well in the glacial deposits?
- Where and what type of water wells exist in my vicinity?
- Where are the groundwater dependent features, for example, trout streams and lakes, and Michigan Natural Features Inventory identified wetlands, located?
- What type of water use is in my area and how much groundwater is being withdrawn?
- What are the hydrogeologic characteristics of my county or watershed?
- Are there any publications with water quality data for groundwater in my area?

How can I obtain components of the inventory and map products?

The inventory and map products are available to end-users in three ways:

- Web-based mapping site hosted by MSU (gwmap.rsgis.msu.edu). The digital data and publications are available for download from this site.
- The digital data are available for download through the State of Michigan, Center for Geographic Information (www.michigan.gov/cgi) for use in a GIS mapping software.
- Digital data provided on compact disc for use with the Map Image Viewer software, an easy-to-use GIS software package for viewing and analyzing spatial data. MSU provides this mechanism. There is a charge for this service for users other than local health departments and the DEQ.



This example glacial yield map highlights some of the interactive map viewer features. The zoom feature allows viewing of smaller geographic areas. At this scale, water well point data can be displayed and queried.

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gwmap.rsgis.msu.edu

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	3	0	0	2	5
Masters	1	0	0	3	4
Ph.D.	2	0	0	2	4
Post-Doc.	0	0	0	0	0
Total	6	0	0	7	13

Notable Awards and Achievements

Landmark laws to protect Michigans water resources were Febuary 27, 2005

After years of debate and contentiousness, landmark laws protecting Michigans water resources were passed by the Legislature last month and signed into law by Governor Granholm February 28. The bi-partisan package of five bills finally delivers on Michigans commitment in 1985 to pass comprehensive legislation that prevents Great Lakes diversions.

Institute Director Jon Bartholic provided testimony to the Senate Natural Resources and Environmental Policy Committee on the current scientific understanding of water resources at public meetings held around the state last summer. These public meetings helped to open the door to eventual passage of this critical legislation.

Michigan will have new needs with the passage of this statutory framework to manage our precious water resources wisely, stated Director Bartholic. I look forward to the Institute supporting implementation of these new laws by providing leadership in science and policy research.

The new laws focus on conserving and protecting state water resources and address six important areas: 1) a new water withdrawal permitting system; 2) uniform water use reporting requirements; 3) adverse impacts of water withdrawals on natural resources; 4) water conservation planning; 5) legislative and public involvement; and 6) future research and policy development. The following highlights the new measures to support and encourage water conservation and sound management of state water resources.

One, the new permitting system requires a permit for large water withdrawals over 2 million gallons per day (new or expanded) from inland lakes, rivers, streams, and groundwater sources. The permittee must also demonstrate no adverse impacts on natural resources. A permit fee of $2,000 will be charged to cover the cost of the program.

A permit for large withdrawals from the Great Lakes is needed for withdrawals over 5 million gallons per day and demonstrate no adverse impacts on natural resources; maximize return flows; show that water efficiency measures have been considered; and show that the proposed use is reasonable under existing Michigan law. Users will be charged a fee of $2,000.

Water bottling facilities will need a permit for new or expanded facilities of over 250,000 gallons per day; demonstrate no adverse impacts on natural resources; and that others riparian rights will not be violated. MDEQ will determine whether restrictions are needed on a facility because of impacts on other riparian owners. Users will be charged a user fee of $5,000.

Two, reporting requirements were made uniform by making agricultural irrigation operators responsible for reporting the specific locations of their wells. In the past agricultural water use reporting was aggregated by township which did not adequately provide specific location information.

Three, the adverse impacts of water withdrawals on natural resources is now defined by statute as any reduction in flow or lake levels causing functional impairments of characteristic fish populations. Such adverse impacts are prohibited. The immediate focus will be on protecting designated trout streams from any adverse impacts, but after two years, these protections will be extended to all lakes, rivers, and streams.

Four, each water use sector (agriculture, mining, industrial, etc.) will be required to prepare generally-accepted water management practices and water users will be encouraged to follow these practices.

Five, legislative and public involvement have a key role in the overall framework for conservation and management of water resources. If the states current ban on diversions is overturned, then the Legislature must approve future diversions. And the Governor is required to hold a public hearing before deciding on whether or not to veto any Great Lakes diversion under the Water Resources Development Act.

Six, the Groundwater Conservation Advisory Council is required to continue its development of sustainability indicators for state water use and assist development of a water withdrawal assessment tool to evaluate the impacts of water withdrawals on natural resources. The Institute anticipates playing a key research support role in developing this assessment tool.

For the first time in state history, a coherent legal framework has been established to conserve and protect water resources, and this is a step that we can all be proud of. The Institute looks forward to providing science and policy research leadership to support implementation of these new laws.

Publications from Prior Projects

1. 2002MI1B ("Natural Resources Integrated Information System") - Conference Proceedings - Bartholic, Jon. 2003. Midwest Groundwater Conference Lecture.
2. 2002MI1B ("Natural Resources Integrated Information System") - Conference Proceedings - Bartholic, Jon. 2003. Digital Watershed: A Nationwide Web Application Tool for Effective Watershed Management presentation in Muskegon, Michigan at the Michigan State of the Lakes Conference, October 2003.
3. 2004MI52B ("Sediment transport modeling using high resolution LIDAR-derived DEMs") - Water

Resources Research Institute Reports - Barber, Christopher P., and Ashton Shortridge. 2004. Terrain representation, scale, and hydrologic modeling: does LiDAR make a difference? pp 16.

4. 2002MI2B ("Water quality trends of Michigan inland lakes and their relationship to ecoregions:1974-2001") - Articles in Refereed Scientific Journals - Nelson, S.A.C., P.A. Soranno, K.S. Cheruvelil, S.A. Batzli and D.L. Skole. 2003. Regional assessment of lake water clarity using satellite remote sensing, Journal of Limnology.
5. 2002MI2B ("Water quality trends of Michigan inland lakes and their relationship to ecoregions:1974-2001") - Articles in Refereed Scientific Journals - Cheruvelil, K.S., N.A. Nate, P.A. Soranno, M.T. Bremigan 2003. A field-test of the unimodal relationship between fish growth and macrophyte cover in lakes, Submitted to Ecological Applications.
6. 2002MI2B ("Water quality trends of Michigan inland lakes and their relationship to ecoregions:1974-2001") - Articles in Refereed Scientific Journals - Nelson, S.A.C., K.S. Cheruvelil, and P.A. Soranno. 2003. Remote sensing of freshwater macrophytes and the influence of lake characteristics. Submitted to Aquatic Botany
7. 2004MI52B ("Sediment transport modeling using high resolution LIDAR-derived DEMs") - Articles in Refereed Scientific Journals - Ouyang, D., J. Bartholic, and J. Selegean. 2003. Assessing Soil Erosion and Sediment Load from Agricultural Croplands in the Great Lakes Basin, The Journal of Great Lakes Research. (In review).
8. 2004MI-ADMIN ("Program Administration Project") - Conference Proceedings - Bartholic, J., 2003. Presented Water Supply and Resource Management at the 45th Annual NARUC Regulatory Studies Program sponsored by the Institute of Public Utilities of Michigan State University. August 10, East Lansing, MI.
9. 2003MI-ADMIN ("Program Administration Project") - Conference Proceedings - Bartholic, J. 2003. Presented Pesticides: Its not just about bugs at the Agricultures Conference on the Environment. March 24, Lansing, MI.
10. 2003MI-ADMIN ("Program Administration Project") - Conference Proceedings - Bartholic, J. 2003. Presented About Digital Watershed at the Lake Michigan State of the Lake 03 Conference. October 21-22, Muskegon, MI
11. 2003MI-ADMIN ("Program Administration Project") - Conference Proceedings - Bartholic, J. 2003. Presented Models of Weather Patterns: Where Does Irrigation Water Go? Consumptive Use at the Michigan Irrigation Association Irrigation Workshop. December 4, Shipshewana, IN.
12. 2004MI42B ("Natural Resources Integrated Information System") - Other Publications - Bartholic, J. 2004. Presented at Michigan Land Use Summit sponsored by the Land Policy Program of Michigan State University. February 2-3, East Lansing, MI.
13. 2004MI-ADMIN ("Program Administration Project") - Other Publications - Bartholic, J. 2004. Presented MSU 2003 Research Results on Drip Irrigation at the Southwest Michigan Irrigation Workshop. January 27-28, Benton Harbor, MI.